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Preliminary Risk Assessment for Parasites in Municipal Sewage Sludge Applied to Land

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Section 405 of the Clean Water Act requires the U.S. Environmental Protection Agency to develop and issue regulations that identify: (1) uses for sludge including disposal; (2) specific factors (including costs) to be taken into account in determining the measures and practices applicable for each use or disposal; and (3) concentrations of pollutants that interfere with each use or disposal. To comply with this mandate, the U.S. EPA has embarked on a program to develop four major technical regulations: Land application, including distribution and marketing; landfilling; incineration and surface disposal. The development of these technical regulations requires a consideration of pathogens as well as chemical constituents of sludge. Public concern related to the reuse and disposal of municipal sludge often focuses on the issue of pathogenic organisms. The purpose of this report is to use the pathogens methodology, Pathogen Risk Assessment for Land Application of Municipal Sludge, to develop a preliminary assessment of risk to human health posed by parasites in municipal sewage sludge applied to land as fertilizer or soil conditioner. The preliminary risk assessment includes a description of the most critical data gaps that must be filled before development of a definitive risk assessment and recommends research priorities.

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PRELIMINARY RISK ASSESSMENT FOR PARASITES IN MUNICIPAL SEWAGE SLUDGE APPLIED TO LAND

Environmental Criteria and Assessment Office
Office of Health and Environmental Assessment
Office of Research and Development
U. S. Environmental Protection Agency
Cincinnati, OH 45268

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PREFACE

Section 405 of the Clean Water Act requires the U.S. Environmental Protection Agency to develop and issue regulations that identify: (1) uses for sludge including disposal; (2) specific factors (including costs) to be taken into account in determining the measures and practices applicable for each use or disposal; and (3) concentrations of pollutants that interfere with each use or disposal. To comply with this mandate, the U.S. EPA has embarked on a program to develop four major technical regulations: land application, including distribution and marketing; landfilling; incineration and surface disposal. The development of these technical regulations requires a consideration of pathogens as well as chemical constituents of sludge. Public concern related to the reuse and disposal of municipal sludge often focuses on the issue of pathogenic organisms. The purpose of this report is to use the pathogens methodology, Pathogen Risk Assessment for Land Application of Municipal Sludge, to develop a preliminary assessment of risk to human health posed by parasites in municipal sewage sludge applied to land as fertilizer or soil conditioner. The preliminary risk assessment includes a description of the most critical data gaps that must be filled before development of a definitive risk assessment and recommends research priorities.

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LIST OF ABBREVIATIONS

D&M	Distribution and marketing
dia	Diameter
g	Gram
ha	Hectare
hr	Hour
m	Meter
MID	Minimum infective dose
min	Minute
NOAA	National Oceanic and Atmospheric Administration
PSRP	Processes to significantly reduce pathogens
sec	Second
USDA	U.S. Department of Agriculture

1. EXECUTIVE SUMMARY

This preliminary risk assessment study focuses on the probability of human infection from protozoa and helminths, usually referred to as parasites, in municipal sludge applied to land. It is based on the Pathogen Risk Assessment computer model and methodology described in Pathogen Risk Assessment for Land Application of Municipal Sludge.

This document reports (1) the results of a literature review designed to find the data on parasites required by the pathogens methodology, and (2) the results of numerous site-specific computer simulations, running the Pathogen Risk Assessment Model with a wide range of values for the parameters required. The parameters required for parasites are (1) density of viable parasites in treated sludge destined for land application; (2) die-off rates in soil, dry particulates, liquid aerosols, and water; (3) dispersion in the environment, i.e., transport in water, soil and air; and (4) minimum infective dose, which for parasites is assumed to be MID=1 since single eggs of helminths and single cysts of protozoa have produced infections in humans. Of these parameters, density is site-specific and requires a standard method for enumerating parasites, die-off rate data are very limited, transport data are essentially non-existent, and infective dose has been determined to be MID=1.

Locations selected for site-specific application of the model include Anderson County, Tennessee; Chaves County, New Mexico; Clinton County, Iowa; Highlands County, Florida; Kern County, California; and Yakima County, Washington. The sites were chosen to provide diversity in geographic location, topography, soil type, rainfall pattern and temperature.

Parasites are of health significance in land application practices because they tend to become concentrated in sludge during sewage treatment processes and because they can remain viable as environmentally stable protozoan cysts or helminth ova for months or years under favorable conditions. Although epidemiological studies suggest little risk to human health from parasites in treated municipal sludge or wastewater applied to land, their low minimum infective dose and persistence in soil mean that the issue cannot be dismissed.

Density and viability of parasites in sludge are site-specific, based on source of wastes, species of parasites present, climate, and efficacy of sludge treatment. Densities of parasites have been reported to be generally higher in sludges from southern than from northern states. However, accurate risk assessment would require site-specific analysis of density levels by standard methods for enumerating parasites in sludges and soil. Parasite densities reported in the literature range from 100-2000 ova/kg dry wt in dried sludge and 0-30,000 cysts or ova/kg in liquid sludge; however, the values are highly dispersed and geometric means are in the range of 200-2000 ova/kg dry wt. According to EPA regulations, composted sludge for distribution and marketing (D&M) must have no more than 1 ovum/g or cyst/g volatile sludge solids. Based on the literature ranges, values suggested for use in the Pathogen Risk Assessment model are 5000 ova or cysts/kg for liquid sludge, 500 ova or cysts/kg for dried sludge and 1000 ova or cysts/kg for composted (D&M) sludge. The value used in the following risk assessment was 5000 ova or cysts/kg for all practices.

During storage under unfavorable conditions, ova and cysts may become inactive (non-infective) before they die. Death may be followed by disintegration. Although some of the studies discussed include information on infectivity, in many cases only viability of eggs and cysts was reported, and some studies reported only occurrence, not viability.

Inactivation of parasites appears to be most closely tied to temperature during treatment or storage, with higher temperatures contributing to increased inactivation. Temperatures in the 45-55°C range are likely to kill resistant parasites within a few hours. Alternate freezing and thawing reduce viability more rapidly and to a greater extent than constant above- or below-freezing temperatures.

Field studies of parasite-contaminated sludge applied to agricultural plots, however, have not produced a direct statistical correlation between viable Ascaris ova concentration and solar radiation, relative humidity or soil temperatures. In fact, no statistical correlation was found between parasite egg concentration and chemical, physical or biological parameters.

Data on die-off rates are very limited, but a published 90% die-off time of 270 days implies an exponential rate of $10^{(-0.000154)}$/hour. Published ranges for die-off are approximately $10^{(-0.0001)}$/hour to $10^{(-0.0005)}$/hour at ambient temperature. Based on these ranges, suggested values in the model for die-off of ova and cysts are:

During application/incorporation
0 for Temp $< 20°C$;
$10^{(-0.000178)}$ or 0.00041/hour for $20 \leq$ Temp < 40;
$10^{(-0.456)}$ or 0.65/hour for Temp ≥ 40;

In moist soil
0 for Temp $< 20°C$ or for 8 hours after irrigation;
$10^{(-0.00023)}$ or 0.000533/hour for $20 \leq$ Temp < 40;
$10^{(-0.667)}$ or 0.7845/hour for $40 \leq$ Temp ≤ 50;
$10^{(-0.125)}$ or 0.25/hour for Temp > 50;

On crop surfaces
$10^{(-0.667)}$ or 0.7845/hour at all temperatures;

In water
$10^{(-0.00023)}$ or 0.000533/hour at all temperatures.

Although detailed data on survival and transport of parasites in soil are lacking, the Pathogen Risk Assessment Model appears to confirm the general observations in the literature that parasites are persistent, justifying land-use restrictions. Model runs implied that restrictions on the consumption of below-ground crops may be overly conservative.

Model runs showed that within narrow limits, the probability of human infection by parasites as a result of exposure to soil contaminated with sewage sludge is proportional to the concentration of organisms in the sludge, the amount of sludge applied and the amount of contaminated soil to which the individual is exposed, either by casual contact or ingestion of food grown in the contaminated soil. Many of the parameters of the model seemed to have little bearing on the probability of infection, apparently because they had no effect on the number of organisms to which the human receptor was exposed in each exposure compartment or they exerted their effect after the time of maximum exposure. The probability of infection was sensitive to the rate of inactivation or die-off of the parasite ova or cysts and to the method of application. According to the model, human exposure via subsurface application of sewage sludge would be unlikely because it is believed that ova or cysts cannot move significant distances through soil.

The model predicted that the most significant potential source of infection would be exposure to runoff water and sediment transported to an onsite pond after rainfall. Model runs indicated that it would be prudent to limit access to runoff water and sediment from a sludge-amended field, either by mulching to reduce runoff, ditching and diking to contain the runoff or restricting access to any onsite ponds receiving runoff.

Various model runs predicted that it was unlikely that a significant number of ova or cysts would be transported off-site either by droplet aerosols or wind-blown dusts. The model also predicted that parasites moving through the soil column into groundwater was unlikely. Therefore, one can infer, based on the model parameters used, that there is relatively little risk to human health from parasitic infection via inhalation of contaminated fugitive dust emissions or ingestion of contaminated groundwater.

Using a benchmark probability of infection of 1×10^{-4} as an indicator of sufficient protection of human health, a waiting period appeared to be unnecessary for consumption of aboveground crops contaminated with 0.1 g soil/crop unit. A waiting period of 18 months appeared to be adequate for below-ground crops, whose consumption is currently forbidden for 5 years after sludge application.

The current version of the Pathogen Risk Assessment Model does not address some of the properties of parasite survival in soil. Mathematical descriptions of the die-off of parasite ova, cysts and oocysts as a function of temperature and moisture are not yet adequate to allow construction of algorithms for die-off rates. It may be appropriate to add a diurnal cycle to the model's temperature algorithm. Other changes may be limited by the constraint that the model should run on a personal computer.

The following research priorities are recommended to allow development of a definitive risk assessment for parasites in land-applied sludge:

For Helminths:

- Standard quantitative methods for examining helminths in sludge and soil samples;
- Data on transport in water, soil and aerosols;
- Die-off rates in water, soil and aerosols;
- The relationship of those decay rates to environmental conditions, previous sludge treatment, method of sludge application and various effects of crop cover.

For Protozoa:

- Quantitative methods for examining protozoa in sludge and soil samples; and

- Quantitative data on occurrence and survivability of protozoa in treated sludge.

If results indicate that protozoa survive in sludge, the following additional research needs become a priority:

- Data on transport in water, soil and aerosols;
- Die-off rates in water, soil and aerosols;
- The relationship of those decay rates to environmental conditions, previous sludge treatment, method of sludge application and various effects of crop cover.

2. INTRODUCTION

This preliminary risk assessment study focuses on the probability of human infection from intestinal protozoa and helminths in municipal sludge applied to land. These two types of microorganisms are usually grouped under the heading of "parasites" (Kowal, 1985). Sludge, a byproduct of sewage treatment, is the mixture of solids and liquids remaining after settling processes remove solids from municipal or domestic wastewater. Secondary and tertiary sludges contain biomass resulting from microbial digestion of the sewage. Being derived from human sanitary wastes, sludge contains microorganisms that colonize humans and can cause infection and disease.

This risk assessment is based on the Pathogen Risk Assessment computer model and methodology described in Pathogen Risk Assessment for Land Application of Municipal Sludge (U.S. EPA, 1990b). The purpose of the model is to determine the probability of infection of a human receptor from pathogens in the land-applied sludge. The model consists of a series of compartments (Table 2-1) representing discrete points in the application pathway. The compartments are the various locations, states or activities in which sludge or sludge-associated pathogens exist; they vary to some extent among practices. Compartments representing sources of human exposure are designated with an asterisk in Table 2-1. In each compartment, pathogens increase, decrease or remain the same in number with time, as specified by "process functions" (growth, die-off or no population changes) and "transfer functions" (movement between compartments). Infection rather than disease is used to measure risk in the methodology, since exposures to parasites may lead to human infection that is asymptomatic (Kowal, 1985). The outputs produced by running the model are numerical values for the probability of a human receptor receiving an exposure in 24 hours exceeding the minimum infective dose (MID). The MID is assumed to be one since single eggs of helminths and single cysts of protozoa have produced infections in humans (Kowal, 1985). The model will run until the day specified or until the number of pathogens in each compartment decreases to <1 at which point the number is rounded to zero.

Two categories of land application are employed in the methodology, (1) agricultural utilization and (2) distribution and marketing (D&M), and the source of parasites is either

TABLE 2-1

COMPARTMENTS INCLUDED IN THE SLUDGE MANAGEMENT PRACTICES

Compartment Name and Number	Liquid Sludge Management Practices			Dried/Composted Sludge Management Practices	
	I	II	III	IV	V
Application	1	1	1	1	1
Incorporation	2	2	2		
Application/Tilling Emissions	3*	3*	3*	3*	3*
Soil Surface	4	4	4	4	4
Particulates	5*	5*	5*	5*	5*
Surface Runoff	6*	6*	6*		
Direct Contact	7*	7*	7*	7*	7*
Subsurface Soil	8	8	8	8	8
Groundwater	9	9	9		
Irrigation Water	10	10	10		
Soil Surface Water	11	11	11	11	11
Offsite Well	12*	12*	12*		
Aerosols	13*	13*	13*		
Crop Surface	14	14	14	14	14
Harvesting	15		15	15	
(Commercial) Crop	16*			16*	
Animal Consumption		17	17		
Meat		18*	18*		
Manure		19	19		
Milk		20*	20*		
Hide		21	21		
Udder		22	22		

*Indicates exposure compartment

liquid or dried/composted municipal sewage sludge. The five municipal sewage-sludge management practices (Table 2-2) included in the model are application of liquid treated sludge (I) for production of commercial crops for human consumption, (II) to grazed pastures, and (III) for production of crops processed before animal consumption; and application of dried or composted sludge (IV) to residential vegetable gardens and (V) to residential lawns. Practices III and V, while ostensibly limited to hay fields and residential lawns, respectively, can be modified by selection of appropriate parameters to represent sludge application on golf courses, parks, roadsides, etc. Although Practice V does not include an onsite pond, the risk to SWIMMER can be modeled by using appropriate parameters in Practice III.

Risk assessment for pathogens in land-applied municipal sludges requires the following input data:

- Types of pathogens and their concentrations in the sludge, their survivabilities, and their infective doses (MID=1 for parasites);
- The sludge reuse/disposal option used and the conditions of sludge application (quantities, frequencies, application method);
- The fate of the pathogens in the environment, i.e., the die-off rate under different conditions including moist soil, dry particulates, droplet aerosols and water; and
- The level of exposure of human receptors to the applied sludge.

This document reports (1) the results of a literature review designed to find the data on parasites required by the pathogens methodology, and (2) the results of numerous computer simulations, running the Pathogen Risk Assessment Model with a wide range of values for the parameters required. Six sites, chosen to provide diversity in geographic location, topography, soil type, rainfall pattern and temperature, were selected for site-specific applications of the model: Anderson County, Tennessee; Chaves County, New Mexico; Clinton County, Iowa; Highlands County, Florida; Kern County, California; and Yakima County, Washington. Because of the unlimited number of possible sites, the final selections were somewhat arbitrary, being based on an attempt to represent different geographic regions and to ensure a variety of weather patterns.

Exposure pathways, i.e., migration routes of parasites from or within the application

TABLE 2-2

SLUDGE MANAGEMENT PRACTICES AND DESCRIPTIONS IN LAND APPLICATION MODEL

PRACTICE	DESCRIPTION
I	Application of Liquid Treated Sludge for Production of Commercial Crops for Human Consumption
II	Application of Liquid Treated Sludge to Grazed Pastures
III	Application of Liquid Treated Sludge for Production of Crops Processed before Animal Consumption
IV	Application of Dried or Composted Sludge to Residential Vegetable Gardens
V	Application of Dried or Composted Sludge to Residential Lawns

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*Two types of sludge are used in this model - liquid and dried/composted. The extent of treatment or conditioning prior to application is variable and must be determined for each case.

site to a receptor, for sludge applied to land include the following:

- Inhalation and ingestion of emissions from application of sludge or tilling of sludge/soil;
- Inhalation and ingestion of windblown or mechanically generated particulates;
- Swimming in a pond fed by surface water runoff;
- Direct contact with sludge-contaminated soil or crops (including grass, vegetables, or forage crops);
- Drinking water from an offsite well;
- Inhalation and subsequent ingestion of aerosols from irrigation;
- Consumption of vegetables grown in sludge-amended soil;
- Consumption of meat or milk from cattle grazing on or consuming forage from sludge-amended fields.

This methodology assumes that exposure to parasites will not result in infection unless the organisms are actually swallowed. Risks due to inhalation of enteric pathogens will be considered only because the organisms can be subsequently swallowed. Disease can result through routes of exposure other than the alimentary tract; calculations of exposure by direct contact in the Pathogen Risk Assessment methodology do not distinguish among routes of infection.

The following human receptors are the exposed individuals whose probability of infection by parasites is calculated by this model:

- Onsite person (ONSITE) who is exposed by ingestion (includes pica in children) or skin penetration of parasites following direct contact with soil, vegetables, or forage or by inhalation and subsequent ingestion of aerosols (particulates or liquid);
- Offsite person (OFFSITE) who is exposed to particulate or liquid aerosols carried by wind;
- Food consumer (EATER) who eats vegetable crops, meat or milk produced on sludge-amended soil;
- Groundwater drinker (DRINKER) who consumes water from a well near but not on the sludge application site;

Pond swimmer (SWIMMER) whose skin is penetrated by parasites or who ingests a small amount of water while swimming in the pond that receives the surface runoff from the application site.

The model conceptualization (U.S. EPA, 1990b) specifies that workers engaged in the transportation, handling and application of liquid sludge are not included as exposed individuals because such activity is an occupational exposure.

The U.S. EPA (1985, 1986) has provided extensive information relevant to the conceptual risk assessment framework for land application of sludge. These key studies address the pathogens associated with sewage sludge, as well as exposure pathways and the potential risks to humans from each of the pathways. Most of that information will not be repeated here. Additional information about the computer model and methodology is available in Volumes I and II of Pathogen Risk Assessment for Land Application of Municipal Sludge (U.S. EPA, 1990b) and in Wilson et al. (1989); a brief overview of the model is included as an Appendix.

3. LITERATURE REVIEW OF PARASITES

A literature search was performed to find the most current information available for the parameters required by the model for simulating land application of sludge. The parameters required for parasites are (1) density of viable parasites in treated sludge destined for land application; (2) die-off rates in soil, dry particulates, liquid aerosols, and water; (3) dispersion in the environment, i.e., transport in air, soil and water; and (4) infective dose, which for parasites is assumed to be MID=1.

Appropriate codes and keyword truncation were used to produce the most effective search strategy for each data base. Table 3-1 lists the computerized data bases queried and the keywords used. The three columns of keywords were "anded" together to produce a set in which at least one keyword in each column was a descriptor or was contained in a retrieved record.

References in review articles and in relevant articles retrieved by the computer search were also evaluated, and names of pertinent authors were searched to find recent papers that may not have been incorporated into online databases.

3.1. SIGNIFICANCE OF INTESTINAL PARASITES

The protozoan pathogens cause a variety of symptoms by colonizing the gastrointestinal tract. Protozoan diseases may be debilitating but are rarely fatal in developed countries. Protozoa are present in sewage and sludge as cysts and oocysts, dormant structures resistant to adverse environmental conditions (U.S. EPA, 1990b).

The pathogenic helminths include a variety of worms, some of which are only incidental parasites of humans. Among them are pinworms, roundworms, whipworms, and a variety of tapeworms. The larval stages of helminths often migrate through the body before maturing in the gut and can cause serious tissue and organ damage. Adult forms primarily cause malnutrition and anemia while residing in the gut. Helminths are present in sewage and sludge as ova. More complete data on pathogenic helminths and protozoa are discussed in Kowal (1985) and U.S. EPA (1985, 1986).

TABLE 3-1

COMPUTER SEARCH STRATEGY

DATA BASES	KEYWORD GROUPS		
AGRICOLA	PARASITE	SURVIVAL	SEWAGE
AGRIS	HELMINTH/HELMINTHES	DISPOSAL	SOIL
BIOSIS	ROUNDWORM	TRANSPORT	AIR
CAB ABSTRACTS	HOOKWORM	FATE	AEROSOL
CRIS/USDA	TAPEWORM	VIABILITY/VIABLE	WATER
ENVIROLINE	CESTODE/CESTODA	LIFE CYCLE	SLUDGE
FSTA	NEMATODE/NEMATODA	MOVEMENT	
NTIS	GIARDIA	DIE-OFF	
POLLUTION ABSTRACTS	CRYPTOSPORIDIUM		
TOXLINE	PROTOZOA		
WATER RESOURCES ABS	TAENIA		
ZOOLOGICAL RECORD	ASCARIS		
	ENTAMOEBA/ENTAMEBA		
	AMEBA/AMOEBA		
	ACANTHAMOEBA/ACANTHAMEBA		

3.1.1. **Reproduction and Life Cycle.** Protozoa typically reproduce asexually, by fission, but many also have sexual cycles in which they form zygotes, which mature to cysts or oocysts (Daly, 1983b). Trophozoites are the active stage of flagellate protozoans in the intestines of infected individuals, whereas sporozoites are the active stage for coccidians. Following a period of reproduction, the trophozoites or sporozoites can become precysts, capable of secreting a tough membrane to protect the parasite (Kowal, 1985). It is these thick-walled, environmentally resistant, dormant structures that are excreted in the feces and are found in sewage and sludge. These forms are capable of causing human infection.

Helminths are parasitic worms that typically reproduce in the gut and generally require more than one host to complete their life cycle. They may have simple life cycles in which humans become infected by ova or larvae produced by the worms. Or, the life cycle may be more complex, requiring several hosts before reaching humans. Typically, the adult tapeworm lives in the gut of the definitive (final) host and sheds fertilized ova, either free or contained in proglottids, in the feces. Helminth ova are the resistant stage found in sludge. The ova are eaten by the intermediate host and develop into larvae, which may form cysts within the tissues of the intermediate host. The definitive host species ingests the infected tissue, and the larva develops into an adult in the gut of this host. An example of this life cycle is the beef tapeworm, Taenia saginata, found in the small intestine of humans. It is obtained through eating poorly cooked beef. The adult tapeworm can attain lengths of ~5 m, containing as many as 2000 proglottids that pass eggs as they move through the lower gastrointestinal tract. These ova must be eaten by herbivores such as cattle to allow further development. The larva released from the egg penetrates the intestine and form a cysticercus in the striated muscle. When ingested by humans, the cysticercus transforms into a mature tapeworm (Daly, 1983a). Rarely, humans have been known to be infected by Taenia ova (Beaver et al., 1984).

Other important parasitic helminths are tissue roundworms that can cause visceral larval migrans or cutaneous larval migrans in humans. Larvae of the dog and cat ascarids Toxocara canis and Toxocara cati can produce visceral larval migrans as they migrate through human tissues, producing inflammatory reactions in organs such as the liver (hepatomegaly) and lungs (pneumonitis). Serious irreversible damage is possible if critical areas such as the nervous system are affected. The life cycle of these nematodes is similar to that of human Ascaris lumbricoides, with the source of infection being ingested soil containing embryonated ova. Children suffering from pica, an abnormal soil-eating behavior, are more likely than adults to acquire this infection. However, for Toxocara, humans are abnormal hosts in whom the life cycle cannot be completed (Daly, 1983a).

Cutaneous larval migrans is a skin inflammation most commonly caused by the hookworm Ancylostoma braziliense. The filariform larvae penetrate the skin and produce lesions within the skin. As they travel around under the skin, the larvae produce an irritative pruritis that leads to scratching and can result in secondary bacterial infections. As is the case with Toxocara, the larvae cannot complete their life cycle in a human host. Other dog hookworms and some other nematodes can also cause cutaneous larval migrans (Daly, 1983a).

3.1.2. **Transmission/Exposure Routes.** Transmission of parasitic infections is usually by one of the following routes: ingestion of contaminated food or water, direct contact with the parasite form in feces, soil or water, or consumption of the undercooked flesh of the host. The modes of transmission for those parasites of concern in sewage sludge are listed in Table 3-2.

Toxoplasma infections are transmitted by direct contact with cat feces or by ingestion of undercooked meat containing the oocyst, but the most hazardous route is transplacental. While typically asymptomatic for most infected individuals, toxoplasmosis during pregnancy can seriously harm the fetus (Hershey and McGregor, 1987).

The transmission potential for Cryptosporidium, a coccidian protozoan, is as yet unknown, although it has been the cause of several outbreaks of waterborne illness (Rose, 1988; Crawford and Vermund, 1988; Hayes et al., 1989). Features of the pathogen's taxonomy and life cycle contribute to the likelihood for waterborne transmission (Current, 1987). Cryptosporidium may be the cause of much of the diarrheal illness in humans and other mammals worldwide. Infected individuals excrete "an environmentally stable oocyst" in feces, and evidence of significant cross-transmission among mammals (wild and domestic animals and humans) suggests the organism is ubiquitous in the environment (Fayer and Ungar, 1986; Current, 1987; Rose, 1988).

Data are as yet insufficient to determine the significance of Cryptosporidium in municipal sewage sludge destined for land application. However, Kayed and Rose (1987)

TABLE 3-2

PATHOGENS OF CONCERN

Pathogen	Common Name or Class	Disease	Nonhuman Reservoir	Human Infective Stage	Mode of Transmission
HELMINTHS - Nematoda					
Ancylostoma duodenale	Hookworm	Hookworm disease		free-living larva	skin penetration, soil contact
Ancyclostoma braziliense	Cat hookworm	Cutaneous larva migrans	cat,dog*	free-living larva	skin penetration, soil contact
Ancylostoma caninum	Dog hookworm	Cutaneous larva migrans	dog*	free-living larva	skin penetration, soil contact
Ascaris lumbricoides	Roundworm	Ascariasis		embryonated ovum	ingestion of water, food, soil
Ascaris suum	Swine roundworm	Ascariasis	pig*	embryonated ovum	ingestion of water, food, soil
Enterobius vermicularis	Pinworm	Enterobiasis		ovum	ingestion of ova
Necator americanus	Hookworm	Necatoriasis		embryonated ovum	skin penetration, soil contact
Strongyloides stercoralis	Threadworm	Strongyloidiasis	dog	free-living larva	skin penetration, soil contact
Toxocara canis	Dog roundworm	Visceral larva migrans	dog*	embryonated ovum	ingestion of water, food, soil
Toxocara cati	Cat roundworm	Visceral larva migrans	cat*	embryonated ovum	ingestion of water, food, soil
Trichuris trichiura	Whipworm	Trichuriasis		ovum	ingestion of food
HELMINTHS - Cestoda					
Echinococcus granulosus	Dog tapeworm	Unilocular hydatid disease	dog*	ovum	ingestion of water, food
Echinococcus multilocularis	Tapeworm	Alveolar hydatid disease	dog, fox	ovum	ingestion of water, food
Hymenolepis nana	Dwarf tapeworm	Taeniasis	rat, mouse	ovum (auto-possible)	ingestion of water, food

TABLE 3-2

PATHOGENS OF CONCERN (continued)

Pathogen	Common Name or Class	Disease	Nonhuman Reservoir	Human Infective Stage	Mode of Transmission
Taenia saginata	Beef tapeworm	Taeniasis		ovum, as well as larva in or from intermediate host	ingestion of water, food
Taenia solium	Pork tapeworm	Taeniasis, cysticerosis		ovum,larva in or from intermediate host	ingestion of water, food
PROTOZOA					
Balantidium coli	Ciliate (dysentery)	Balantidiasis	pigs, other mammals	cyst	ingestion of water, food
Cryptosporidium parvum	Sporozoan (Coccidia)	Cryptosporidiosis	cattle	oocyst	contact, ingestion of water, food
Dientamoeba fragilis	Amoeba	Amebiasis		unknown	ingestion of water, food
Entamoeba histolytica	Amoeba	Amebiasis (amebic dysentery)		cyst	ingestion of water, food
Giardia lamblia	Flagellate	Giardiasis	mammals	cyst	contact, ingestion of water, food
Isospora belli	Sporozoan (Coccidia)		dog	oocyst	ingestion of water, food
Isospora hominis	Sporozoan (Coccidia)		dog	oocyst	ingestion of water, food
Toxoplasma gondii	Sporozoan (Coccidia)	Toxoplasmosis	cat	oocyst	ingestion of water, food

Source: Kowal, 1985; U.S. EPA, 1988; Sorber and Moore, 1986

* Definitive host; humans only incidentally infested

reported Cryptosporidium oocyst concentrations in anaerobically digested sludges ranging from 1250-38,700/g dry wt. Madore et al. (1987) found that Cryptosporidium oocyst removal efficiency by sewage treatment, using activated sludge, approached 79%. Sewage treatment utilizing sand filtration in conjunction with activated sludge resulted in lower levels of oocysts (10/L) in finished effluent than treatment using activated sludge treatment only (1300 oocysts/L), suggesting that the filtered oocysts would be found in the sludge. The importance of Cryptosporidium as a waterborne pathogen and its similarity to Giardia suggests further studies are needed to clarify its survivability in water and wastewater treatment processes. There is some disagreement over whether Cryptosporidium or Giardia duodenalis is the more common intestinal parasite and which has the greater potential for causing waterborne disease (Rose, 1988; Sykora et al., 1990).

3.1.3. Occurrence of Parasites in Sludge. Several literature reviews have included surveys of parasites present in sludge at different stages of treatment, and most discuss the diseases associated with these pathogen populations (WHO, 1981; Kowal, 1982, 1985; U.S. EPA, 1986). Several reviews have summarized information on parasites in sludge applied to land: Kowal (1985), Sorber and Moore (1986), Pedersen (1981), Reimers et al. (1981, 1986, 1990), Yanko (1988), and U.S. EPA (1985). Most of that information will not be repeated here, although conclusions derived in these reviews are included in the relevant sections of this document.

Table 3-2 lists the protozoa and helminths most commonly found in sewage sludge and wastewater that are significant human pathogens. For a descriptive summary of these parasites, their life cycles, and the symptoms of infection in humans, see Kowal (1985). His review provides information on the occurrence and viability of pathogens in sludge and in the environment following application. Information on their levels, survival, and behavior in soil, groundwater, surface water, aerosols and animals is discussed; and available data on infective dose, risk of infection and epidemiology of these agents are summarized.

3.1.4. Epidemiology. Epidemiological studies have suggested little risk to human health from parasites in municipal sludge or wastewater applied to land. The low MID for parasites, however, and the persistence of some parasites, particularly helminths, in soil suggests that all questions of public health risk have not been answered (Kowal and Pahren, 1982).

Yanko (1988) studied the occurrence of pathogens in 498 samples of municipal composts, air-dried and heat-treated sludge products, often referred to as distributed and marketed (D&M) sludge. Products sampled weekly for one year were from a windrow composting facility and from an aerated static pile composting facility. Final sludge products from 24 other municipalities were sampled bimonthly for a year. No protozoan cysts were found in the samples, and helminth ova, while regularly detected, were not viable. Trichuris and Ascaris were the helminth ova most commonly found, and evidence suggests that many of the Trichurus ova were from non-human sources. Hymenolepis and Toxocara ova were detected infrequently. No health hazards from parasites were found associated with the treated sludge products.

With respect to wastewater, Clark et al. (1981) reported results of a prospective seroepidemiological study of municipal wastewater workers and controls in Memphis, Cincinnati, and Chicago. They concluded that wastewater workers were not subject to "any detectable risks due to parasites in wastewater."

Amebic infections have been linked epidemiologically with vegetables fertilized with night soil or irrigated with untreated wastewater (Bryan, 1977; Geldreich and Bordner, 1971). When raw wastewater was used to irrigate fields on Israeli kibbutzim, however, no excess of enteric diseases was found (Shuval and Fattal, 1980).

The occurrence of giardiasis is common and may be of epidemic proportions due to infection acquired by ingesting Giardia cysts in public water supplies or in surface water (Meyer and Radulescu, 1979). The potential for waterborne disease transmission of Cryptosporidium may equal or exceed that of Giardia (Rose, 1988; Current, 1987). In addition, its transmission by the fecal-oral route from host to host by means of its environmentally stable oocyst and its capacity for auto-infection makes its epidemiology of extreme importance (Rose, 1988; Current, 1987).

Dorn et al. (1985) concluded that health risks to humans and animals on Ohio farms receiving yearly applications of municipal sewage sludge were not significantly different from those on control farms. Sludge was applied at relatively low rates of 2-10 dry metric tons/hectare(ha)/year in accordance with U.S. EPA guidelines. The authors caution that higher application rates, higher concentrations of disease organisms in the sludge or increases in treated acreage/farm may produce different health risks. In fact, Fertig and

Dorn (1985) summarized an epidemiological investigation of an outbreak of *Taenia saginata* cysticercosis on an Ohio cattle farm, concluding that it is likely that the infection of the seven slaughtered cattle was associated with application of municipal sewage sludge.

Wallis et al. (1984) concluded that health risks were no greater from sludged fields than from the control hayfield and pasture receiving no sludge application. They recorded decreases in numbers of parasite eggs from 11,000 eggs/kg dry wt in the initial sludge applied to a grass plot to 7000 parasite eggs/kg dry wt after 7 days. No eggs were found at 43, 84 or 118 days following sludge application. Sludge injected into the soil showed reductions from the initial 11,000 eggs/kg dry wt to almost none within 4 weeks. Storey and Phillips (1985), however, found that *Taenia saginata* and *Ascaris lumbricoides* ova could be washed into the soil where they were afforded protection from radiation and desiccation, increasing survival with increasing depth in the soil profile.

In Europe, researchers have concluded that the chief hazards of sludge application for agriculture are from *Salmonella* spp. and from the ova of *Taenia saginata* and *Ascaris* spp. (Block et al., 1986). Matching the degree of pathogen reduction with restrictions on use of the sludged land is the method used to eliminate risks. Since the use of disinfected sludge has the fewest restrictions, pasteurization of sludge at 70°C for 30 minutes has been developed in Switzerland (where it is now required) and in Germany to protect cattle from salmonellosis (Pike et al., 1988).

Burger (1984) reviewed the prevalence of *Taenia saginata* in humans in Europe; it ranged from a low of 0.013% in an unselected population in Poland to 8.04% in clinic patients in Turkey. The prevalence of cysticercosis (the larval stage) in cattle ranged from 0.13% in Cuba to 4.2% in Sudan. Insufficient data on infectivity of *T. saginata* eggs allow only a recommendation to prohibit grazing by cattle for at least 4 months following spring application of sludge to pastures and longer during cooler seasons in a moderate climate.

3.2. SURVIVAL IN TREATMENT PROCESSES AND DENSITY IN TREATED SLUDGE

The density of parasites in municipal sludge (Table 3-3) is site-specific, being related to the population served by the sewage treatment system, i.e., source of the wastes, species of parasites present, geographic area, and season or climate. Density and viability of parasite species are also dependent on the type of sludge treatment. Primary sludge has received primary treatment such as screening and settling; secondary sludge is produced by biological waste treatment, or secondary treatment; primary and secondary sludge are combined to produce mixed sludge (U.S. EPA, 1985). Studies of municipal sludges from southern states showed that 99% of primary sludges and 89% of final sludges contained large numbers of viable parasite cysts and ova (Reimers et al., 1981; Leftwich et al., 1981).

3.2.1. Survival in Treatment Processes. Ward et al. (1984) summarized the reductions of parasites in various processes to significantly reduce pathogens (PSRP) expressed as $\log_{10}$: mesophilic anaerobic digestion, 0.5; aerobic digestion, 0.5; composting, 2-4; air drying, 0.5-4; and lime stabilization, 0.5.

Pedersen (1981) reviewed the literature concerning parasites in municipal wastewater sludge and concluded that digestion does not effectively reduce levels of parasites in sludge, but that sludge lagooning could produce a 1-log reduction of parasitic ova if carried out for >6 months at temperatures >20°C or for 3 years at temperatures <20°C.

Reimers et al. (1990) found that Ascaris suum eggs in lagoon-stored sludge in Louisiana and Texas were inactivated after 15 months. Die-off of Ascaris in municipal sludge appeared to be a function of temperature except in petroleum-contaminated sludge.

Information on survivability of Giardia and Cryptosporidium in treated sludge is lacking, but waterborne outbreaks of cryptosporidiosis are possible when Cryptosporidium oocysts, resistant to routinely-used disinfectants, escape filtration (Fayer and Ungar, 1986; Current, 1987). A survey of one drinking water treatment plant found that a large number of oocysts were recovered off the filter, indicating concentration of oocysts by filtration and reduction in finished water of as much as 91% (Rose, 1988). An outbreak of cryptosporidiosis in Carrollton, GA was linked to oocysts in drinking water that had been through the disinfection process (Hayes et al., 1989).

TABLE 3-3

CONCENTRATION, VIABILITY, AND SURVIVABILITY OF PARASITES IN SLUDGE

Pathogen	Density in Treated Sludge (Mean ova/ kg dry wt)	Viability	Survivability	Reference
HELMINTHS - Nematoda				
	11,000 (digested, lagooned);			Wallis, 1984
	100-2000 D&M	0%		Yanko, 1988
Ancylostoma duodenale				
Ancylostoma braziliense				
Ancylostoma caninum				
Ascaris lumbricoides	(*Ascaris* spp.) 9600 southern states; 2030 Chicago; 565 northern states, in of final sludges; geometric mean of 1360 in secondary sludges	69% 64% 48%	15 years	Reimers et al., 1981; Kowal, 1985; Arther et al., 1981; Reimers et al., 1986
Ascaris suum				
Enterobius vermicularis				
Necator americanus				
Strongyloides stercoralis				

TABLE 3-3

CONCENTRATION, VIABILITY, AND SURVIVABILITY OF PARASITES IN SLUDGE (continued)

Pathogen	Density in Treated Sludge (Mean ova/ kg dry wt)	Viability	Survivability	Reference
Toxocara canis	(Toxcocara spp.) 700 southern states; 1730 Chicago; 370 northern states, in of final sludges; geometric mean of 280 in secondary sludges	52% 53%		Reimers et al., 1981; Arther et al., 1981; Reimers et al., 1986
Toxocara cati		55%		
Trichuris trichiura	265 northern states, in 22% of final sludges; max of 7700 and geometric mean of <10 in secondary sludges		6 years (in soil)	Seattle Metro, 1983; Reimers et al., 1981, 1986
HELMINTHS - Cestoda				
Echinococcus granulosus				
Echinococcus multilocularis				
Hymenolepis nana				
Taenia saginata				
Taenia solium				

TABLE 3-3

CONCENTRATION, VIABILITY, AND SURVIVABILITY
OF PARASITES IN SLUDGE (continued)

Pathogen	Density in Treated Sludge (Mean cysts/ kg dry wt)	Viability	Survivability	Reference
PROTOZOA	None detected in D&M sludge		Max: 10- days (on (on soil); common max: 2 days (soil)	Yanko, 1988; Kowal, 1985
Balantidium coli				
Cryptosporidium parvum	1250-38,700 oocysts/g dry wt in anaerobically digested sludge; range of 140-4000 oocysts/L in treated sewage effluence (activated sludge)		>140days in water (laboratory study)	Kayed and Rose, 1987; Current, 1987; Madore et al., 1987
Dientamoeba fragilis				
Entamoeba histolytica			18-24 hours (dry soil); 42-72 hours (moist soil); 8-10 days (damp loam and sand); 153 days (water)	Rudolfs et al., 1951; Beaver and Deschamps, 1949; Mitchell, 1972
Giardia lamblia	70-30,000 cysts/L; max 44 cysts/L in treatment plant effluent; avg concn 387-1723 cysts/L in liquid sludge		1 year in liquefied feces stored at 4°C; <24hours (air-dried at 4°C or 21°C); <24hours (artificial sea water at 4°C)	Sykora, 1990; Craft, 1982; Jarroll et al., 1984
Isospora belli				
Isospora hominis				
Toxoplasma gondii			(Toxoplasma spp.) 334-410 days	Frenkel et al., 1975

Source: Jakubowski, 1990; Kowal, 1985; U.S. EPA, 1988; Sorber and Moore, 1986

Sykora et al. (1990) determined the occurrence of Giardia cysts following wastewater treatment in eleven cities across the United States. Occurrence in sludges, determined by direct count (centrifugation), ranged from 70-30,000 cysts/L. Giardia cysts were present in all raw sewage samples, but only half the wastewater treatment plant effluents contained cysts, with maximum counts of 44 cysts/L. Higher cyst concentrations in raw wastewater during the colder months may be due to factors such as higher rates of infection, increased survival of cysts and lower settling rates at lower temperatures (Jakubowski et al., 1990). McHarry (1984) detected Giardia in effluent from sewage treatment plants in Illinois to be ~ 1 cyst/L. Giardia cysts were found to be infective to rats after one year's storage in liquefied feces at 4°C (Craft, 1982).

Schwartzbrod et al. (1989) compared the effects of wastewater treatments on helminth eggs; activated sludge, lagoon treatment and sand filtration reduced the level of helminth eggs by 77.7%, 100% and 98.8%, respectively, in the final effluent destined to be used for crop irrigation. This finding confirms the typical results: concentration of parasites in sludge and relatively low density or absence in wastewater effluent. However, the authors note that the contaminated sludge poses a problem. In addition, they point out that they did not determine the viability and infectivity of the eggs.

Leftwich et al. (1981) evaluated domestic wastewater treatment processes with respect to their ability to inactivate parasites. They considered removal processes, stabilization processes, and decontamination or inactivation processes. In general, aerobic and anaerobic processes are lethal to parasite eggs if carried out at >55°C. Likewise, composting is effective for inactivating eggs if all matter reaches 60°C for at least 2 hours. Drying beds are most effective if moisture is reduced to $\leq$5%.

Pike and associates (1988) determined that complete destruction of viable Ascaris ova was possible only by digestion at 49°C or by heating for 15 minutes at 55°C. Recovery of viable ova from anaerobically digested sludge was significantly affected by temperature of digestion--63% at 35°C but only 0.6% at 49°C--but not by retention period. Digestion alone reduced viability of the recovered ova only slightly. Heating alone also had little effect at temperatures below 51°C for 1 hour, but heating to 55°C for 15 minutes resulted in no viable ova being recovered. When heat treatment reduced viability of Ascaris suum incompletely, subsequent digestion at 35°C further reduced viability.

The results of Pike et al. (1988) closely parallel those of Arther et al. (1981), who found that ova of four genera of parasites survived anaerobic sludge digestion and lagooning by a Chicago sanitary district treatment plant: *Ascaris* spp., *Toxocara* spp., *Toxascaris leonina* and *Trichuris* spp. (see Table 3-3). Viabilities following treatment ranged from 20-64%.

Black et al. (1982) studied the effects of mesothermic anaerobic or aerobic sludge digestion on survivability and viability of eggs from *Ascaris suum*, *Toxocara canis*, *Trichuris vulpis*, *Trichuris suis* and *Hymenolepis diminuta*. Anaerobic digestion destroyed 23% of *Ascaris* eggs, and the aerobic digestion destruction was 38%. *Trichuris* eggs were not destroyed by anaerobic digestion, but 11% of the eggs were destroyed by aerobic digestion. *Toxocara* eggs were destroyed by neither method. The viability of those *Ascaris* and *Toxocara* eggs surviving digestion was not affected, but aerobic digestion decreased the viabilities of *Trichuris* eggs.

Mbela et al. (1990) assessed temperature effects on *Ascaris* ova viability following aerobic and anaerobic digestion of municipal sludges. Both aerobic and anaerobic digestion processes fail to inactivate *Ascaris* eggs in the 25-35°C temperature range (Reyes et al, 1963; Reimers et al., 1987). They concluded that high temperature is a significant factor in the inactivation of pathogens. Increasing detention times from 10 to 31 days while maintaining constant temperature increased *Ascaris* inactivation from 7% to 16% by anaerobic digestion. Aerobic digestion at 35°C and 45°C, with a 10-day detention period, decreased viability by 57% and 82%, respectively. Temperatures of 45-55°C achieved complete inactivation of *Ascaris* ova within two days. Liming and caustic stabilization increased inactivation; temperatures >35°C for sludge digestion coupled with ≤1000 mg lime/g sludge solids completely destroyed *Ascaris* eggs.

O'Donnell et al. (1984) performed controlled laboratory studies of lagooning of sludge. Results indicated that viability and infectivity of eggs were related to storage temperature, with eggs stored at a higher temperature (25°C) becoming nonviable in 10-16 months whereas those eggs held at 4°C were viable and infective at 25 months.

Storey (1987) also concluded that temperature was the major controlling factor in the survival of *Taenia saginata* eggs during simulated sewage treatment processes. Eggs survived treatment at 55°C for only a few hours, and eggs treated at 35°C were killed faster than those at 20°C.

3.2.2. Density of Parasites in Treated Sludge. Since densities of parasites in sludge vary by source and treatment method, there is no true representative parasite concentration for any given PSRP treatment or source of sludge destined for land application. For the most accurate risk assessment, parasite density should be tested by a standard method for a given source of sludge, i.e., a given treatment plant and treatment method. Reimers and associates (1990) and Little et al. (1988) have developed methods for enumerating parasites in sludges and soil, but widely-accepted standard methods would make comparisons of results across studies more meaningful.

Densities of helminth ova in positive samples of distributed and marketed sludge ranged from 0.1-2 ova/g dry wt (100-2000 ova/kg dry wt) (Yanko, 1988).

Pedersen (1981) critically reviewed the original literature detailing quantitatively the density levels of pathogenic organisms in municipal wastewater sludge and septage. He evaluated conventional municipal sludge stabilization and dewatering processes for their effectiveness in reducing those density levels. U.S. EPA (1985), summarizing the results of Pedersen (1981), warns of several qualifications relative to data quality: laboratory studies may not adequately mimic operations at full-scale treatment plants; seeded pathogen behavior may not represent that of naturally occurring organisms; operating conditions during data collection and pathogen numbers reported are uncertain; and there is inconsistency relative to die-off rates during sludge stabilization.

Reimers et al. (1981, 1986, 1990) investigated parasite density in southern sludges, northern sludges, and lagooned sludges, respectively, and the effectiveness of disinfection techniques on their inactivation. Levels of viable helminth ova were typically somewhat lower in northern sludges than in southern sludges for some species, and densities of T. trichiura varied inversely with population size served by the treatment facility (Reimers et al., 1981, 1986).

Reimers and associates (1986) conducted a study of parasites in municipal wastewater sludges from treatment plants in four northern states. In approximately 90% of the sludge samples, they found resistant stages of twenty types of parasites. The most common were Ascaris spp., Trichuris trichiura, Trichuris vulpis and Toxocara spp., with one or more of these parasites detected in 89% of the samples examined. The geometric mean density of eggs was determined for each of these four parasites in sludge samples destined for disposal: 565, 265, 270 and 370 eggs/kg dry wt, respectively (see Table 3-3). *Ascaris* eggs occurred in final sludges at higher densities than the eggs of the other three parasites. Although the authors gave no confidence limits, they stated that there were no significant differences between geometric mean densities of total eggs in aerobic and anaerobic sludges (3000 and 2150 for *Ascaris*, 460 and 600 for *T*. *trichiura*, 345 and 485 for *T*. *vulpis*, 1410 and 1155 for *Toxocara*, respectively). However, there were fewer viable *Ascaris* and *Toxocara* eggs in anaerobic sludges (1720 and 740, respectively) than in aerobic sludges (4090 and 1320, respectively). The authors suggested this effect may be a result of the higher temperature (35-40°C) typical of anaerobic digestion than the typical ambient temperature of aerobic digestion. Viability of these four parasites was determined in samples of undigested, digester and postdigestion sludge and also for the total of all three sludge types. The ratio of geometric means of viable eggs to total eggs (viable and nonviable) in the total of all three sludge types is 710/1000 eggs/kg dry wt of sludge for *Ascaris*, 400/440 for *Trichuris trichiura*, 370/400 for *Trichuris vulpis*, and 670/880 for *Toxocara* (see Table 3-3). The ratio of viable to total eggs in all sludge samples from the four northern states is 1400/1900 eggs/kg dry wt of sludge for *Ascaris*, 200/380 for *T*. *trichiura*, 260/290 for *T*. *vulpis*, and 1100/1400 for *Toxocara* (see Table 3-3). A similar comparison of sludge samples from five southern states showed a significantly higher density of all parasites except *Toxocara*, with ratios of geometric means of viable to total eggs of 2500/2800 eggs/kg dry wt of sludge for *Ascaris*, 880/910 for *T*. *trichiura*, 430/470 for *T*. *vulpis*, and 680/790 for *Toxocara*.

Sykora et al. (1990) determined the density of *Giardia* cysts following wastewater treatment in eleven cities and found the highest average concentration (1723 cysts/L, or ~1723 cysts/kg wet wt) was from Pennsylvania samples of sludge that were dewatered but not digested; the lowest average concentration was 387 cysts/L (or ~387 cysts/kg wet wt) in samples from the Illinois plant. *Giardia* cysts were detected in the wastewater treatment plant effluents, with maximum counts of 44 cysts/L.

3.3. VIABILITY AND SURVIVABILITY IN SOIL AND WATER

Microorganisms are inactivated in soil at rates that vary with the type of organism, the degree of predation by other microorganisms, the amount of sunlight, and the physical and chemical composition of the soil, including moisture content, pH and temperature (Gerba et al., 1975; Kowal, 1985). Moist, cold soils contribute to increased survival time of protozoan cysts and helminth ova; therefore, soils with a higher percentage of organic matter, which have a greater water-holding capacity, may be more conducive to pathogen survival. Protozoan cysts are extremely sensitive to drying. Likewise, helminth eggs and larvae are susceptible to die-off when exposed to desiccation and sunlight, but in cool, moist soil they may remain infective for several years (Kowal, 1985).

Storey and Phillips (1985) found that the survival of T. saginata and A. lumbricoides ova, introduced into the upper 1 cm of soil, increased at increasing depth of the soil profile. The ova survived longer at the lower levels of the soil profile. At levels below 12 cm, the number of T. saginata eggs surviving at 200 days was only slightly reduced from the initial number at the beginning of the experiment.

Reimers et al. (1986) noted that field studies adequately describing parasite egg survival following land application are lacking. These authors indicated that once applied to land, viable helminth eggs may develop into the infective stage. The limited data available suggest that the more resistant eggs (e.g., Ascaris) may survive for years.

With helminths having the longest survival times of the microorganisms of concern, ova of Toxocara and Ascaris have been shown to persist in soil or on pasture for several years. Ascaris has been called the most hardy and resistant of all excreted pathogens (Feachem et al., 1983) with survival times in soil of up to 10-12 years (Brudastov et al., 1970; Oganov et al., 1975). In addition, many sewage treatment methods serve to concentrate Ascaris eggs in the sludge. Lack of accurate and consistent quantitative data on the survival of parasites under land application conditions prompted the U.S. EPA to investigate Ascaris ova survival following land application of municipal wastewater treatment plant sludge (Jakubowski, 1988). Despite problems associated with field studies, results indicated that infective Ascaris eggs survived throughout the 3-year duration of the study. Sludge applied to the surface grass plots produced inactivation of Ascaris ova more rapidly than either subsurface or tilled applications.

Leftwich et al. (1988b) studied parasite survival in anaerobically digested sludge, spiked with Ascaris eggs, applied to agricultural plots in Ohio, Texas and Louisiana. They found that the concentration of Ascaris ova decreased $>90\%$ on untilled, grassed plots, a fact possibly attributable to biological activity and lower, freezing soil temperatures. Incorporation into soil increased survival of the parasites. Although a laboratory experiment showed that survival was greatly reduced at extremely low soil moisture (Leftwich et al., 1988a), under field conditions no statistical correlation was obtained between soil moisture and survival. The authors were unable to draw a direct statistical correlation between viable Ascaris ova concentration and solar radiation, relative humidity or soil temperatures. In fact, no statistical correlation was found between parasite egg concentration and chemical, physical or biological parameters.

Grenfell et al. (1986) also conclude that quantitative analysis of field data fails to show that mortality of infective larvae of Ostertagia ostertagi and Cooperia oncophora, parasitic gastrointestinal nematodes of cattle, varies with climatic parameters, despite that generally widespread view in the literature.

Repeated freezing and thawing of soil samples spiked with Ascaris ova reduced egg viability more rapidly and to a greater extent than did constant room temperature (controls) or below-freezing temperatures (Leftwich et al., 1988a). Viable Ascaris eggs in anaerobic digested sludge and in sediment were reduced by 100% within 6 weeks when spiked in soils of 4%, 10% and 20% moisture and subjected to freeze-thaw conditions. The lower the soil moisture, the greater was the reduction in percentage viable Ascaris ova, regardless of temperature.

Burger (1984) found that Taenia saginata eggs survived differentially depending on the season of contamination of the site. The shortest survival time, 4-8 days, occurred in summer when egg-contaminated soil was exposed to the sun (Soviet Union). The longest survival time was 365 days (Kenya) when eggs were applied to open pasture (infectivity unknown). Burger concludes that the time interval between sludge application and introduction of cattle to the pasture should be at least four months during seasons of pasture growth and longer during the cooler seasons in the northern European Community.

In a study of the development and survival of Trichuris suis ova on pasture plots in southern England, Burden and Hammet (1979) found that ova required 62-90 weeks to develop to the infective stage (embryonation). The rate was dependent on temperature, assuming adequate moisture and oxygen. There was little if any development during the winter. Most susceptible to adverse environmental conditions were the early developmental stages. The highest percentage of ova perished in the plots contaminated during the summer drought of 1975 when maximum air temperatures were above 20°C. Following development to the infective stage, ova survived at least two years.

Burden et al. (1976) studied the closely-related *Trichuris trichiura* and found a relatively rapid death rate of ova in soil in southeast England. During an 18-month observation period, 80% of the eggs died.

Data on survival of parasites in water is very limited. *Entamoeba histolytica* survived 153 days in distilled water at temperatures ranging from 12-22°C and the same length of time in natural waters, but with a decrease of 30% for each 10°C rise in temperature (Mitchell, 1972). These data are generally confirmed by Grenfell et al. (1986), who found that the optimal survival rate for *Ostertagia ostertagi* in water is in the range of 0-15°C with higher die-off rates above and below this range.

There is abundant evidence that *Cryptosporidium* oocysts and *Giardia* cysts persist in water. *Cryptosporidium* oocysts have been identified in surface water (Madore et al., 1987; Crawford and Vermund, 1988) and in a filtered, treated public water supply (Hayes et al., 1989). *Giardia* cysts survive relatively long periods in water, particularly at temperatures below 20°C; above 20°C, cyst inactivation is rather rapid (Jakubowski, 1990). Evidence suggests that *Giardia* cysts in water survive best at 4-8°C (Jakubowski, 1990). Jarroll et al. (1984) reported that cysts did not survive when *Giardia* were exposed for 24 hours to artificial sea water at 4°C or to air-drying at 4°C or 21°C.

Extremes in temperature can reduce oocyst viability. Tzipori (1983) reported that freeze-drying destroyed infectivity of *Cryptosporidium* oocysts as did 30-minute exposure to temperatures below freezing and above 65°C. Laboratory studies have shown that *Cryptosporidium* oocysts stored in containers that exclude air can remain viable for 8-9 months, but excystation seems to occur soon after exposure to air (Tzipori, 1983). Quantitative data on die-off rates in water or soil were not found.

3.4. TRANSPORT

3.4.1. Transport in Soil. It is assumed in the model that pathogens are distributed in the upper soil layer by incorporation and tilling. However, materials in the soil can also be transported by water moving through the soil. This movement occurs through pores, spaces between the particles or grains of soil. Soil pores are generally classified as macropores (>62 μm) or micropores; because water is bound tightly to the surface of the grains and nearly fills micropores, the bulk of water movement is in macropores. Downward bulk transport of water may occur as a result of gravity. Bulk water movement occurs only when the amount of water in the soil exceeds the field capacity. In this case, the path of the water is tortuous because pores are not arranged in straight channels. There may also be upward and horizontal movement as a result of capillarity.

Particulate matter suspended in soil water can be transported as the water moves. Particulates entering soil pores may become lodged because they are too large to move through the pores or because of electrostatic binding to soil particles. Thus bulk transport of particulates occurs more readily in macropores, cracks and channels than in micropores. Capillarity is less likely to transport large particulate matter for significant distances because it occurs mainly in the micropores, which are too small for large particles.

Protozoan cysts (~5-25 μm dia) and helminth ova (~15-80 μm dia) are large enough that they exhibit very little migration through soil (U.S. EPA, 1985). They do not move vertically into groundwater because of the physical barrier provided by the soil, unless there are vertical cracks or fissures. In the Seattle Metro study (1983), no appreciable downward movement of Ascaris ova occurred after 15 days, nor were Ascaris or hookworm eggs or Entamoeba histolytica cysts able to pass through 24 inches of sand.

Sorber and Moore (1986) conclude in their critical literature review that "there are essentially no data available in the published literature that would permit estimating transport rates for pathogens from sludge-amended soils." They go on to indicate that the size of protozoan cysts and helminth ova appears to prevent the vertical migration of these parasites from sludge-amended soil, but no studies designed to resolve this issue were found in their review of the literature. However, Storey and Phillips (1985) measured the rate of transport of T. saginata (~30 μm dia) and A. lumbricoides (~50 μm dia) ova in laboratory soil columns. The mean distances traveled in 72 hours by the smaller T. saginata eggs and the larger A. lumbricoides eggs were 2.21 cm and 1.78 cm, respectively, with a drip rate of 0.25 mL/minute, and 2.54 cm and 2.14 cm, respectively, with a drip rate of 0.5 mL/minute. The soil columns were 1 cm in diameter (0.79 cm^2 in area), so the amount of water percolating through them at 0.25 ml/min was 0.25/0.79 = 0.316 cm/min, or 1367 cm in 72 hr. Therefore the relative rate of migration of T. saginata was 2.21/1367 = 1.62×10^{-3}, and the relative rate of migration of A. lumbricoides was 1.78/1367 = 1.30×10^{-3}. From these ratios, a rough calculation could be made of the time required to transport parasite ova through soil. Even if the relative rate of migration were as high as 0.01 and all rain water were to pass through the soil layer containing the ova, the time required to move the ova 100 cm would be greater than 65 years if the annual rainfall averaged 60 inches.

Results from the current literature search confirm the dearth of data with respect to the pathogens listed in Table 3-2. However, there have been a few recent reports on other parasites that may be useful as representatives of the group.

Krecek and Murrell (1988) observed that larvae of Ostertagia ostertagi migrated at least 15 cm down into the soil, moved laterally around a barrier and subsequently returned to the surface grass within 5 weeks after the beginning of the experiment. The total distance covered was >30 cm. Bovine fecal pats containing 200,000 eggs were placed on pasture whose base soil was composed of 72% sand, 20% silt and 8% clay. This capability for vertical soil migration and return to surface herbage raises the issue of the epidemiological significance of soil sequestration during periods of environmental stress as a reservoir of Ostertagia. The authors made no determinations of total numbers of larvae re-emerging onto grass. Krecek and Murrell (1988) also reviewed other studies of larval migration in soil and found results to be inconsistent: free-living third-stage larvae did migrate but authors differed in their conclusions about the epidemiological importance of such migration.

Free-living larval forms may move through the surface soil, but these movements are usually active rather than a result of passive transport. Larval migration in soil tends to keep the pathogens near or above the surface, where they are more likely to encounter a suitable host.

Altaif and Yakoob (1987) studied the survival of Haemonchus contortus infective larvae on soil and pasture in Iraq for a period of 12 months. The authors found little evidence of migration of infective larvae in the soil; the majority of larvae of this parasitic gastrointestinal nematode of sheep and goats was discovered in the herbage.

Grenfell et al. (1986) analyzed the survival and migration rates of the infective stages of *Ostertagia ostertagi* and *Cooperia oncophora*, parasitic gastrointestinal nematodes of cattle. They determined, by use of a mathematical model of larval demography, maximum-likelihood estimates of mortality rates of larvae as 0.0284/day in feces and on herbage as 0.0087/day. Average migration rate from feces to herbage in the temperate climate of northern Europe was estimated as 0.00884/day. The life-span of the 3rd-stage larvae (L_3) may be 1-2 years.

Burden and Hammet (1979) recovered *Trichuris suis* ova from contaminated pasture plots at all depths sampled--0-10 cm, 10-20 cm, and 20-30 cm--for the 30-month duration of the test. The samples demonstrated that *T. suis* ova did not leach rapidly through the chalky/flinty soil at Compton in southern England but that they remained available to pigs grazing the plots up to 30 months later. In some of the samples, the majority of ova were located in the 20-30 cm fraction, presumably because the ova were washed down the cracks and fissures that were common on the plots following periods of hot, dry weather.

3.4.2. Transport in Surface Runoff. Whenever the amount of water applied to the land surface is greater than can be absorbed by the soil or soil cover, water will pool on the surface or run off to a lower point on the surface. Microorganisms, along with other particulates in the soil, can be suspended in this surface water and transported as surface runoff. In the Pathogen Risk Assessment Model, it is assumed that runoff occurs only after rainfall, because it is required that irrigation be limited to prevent runoff. In addition, it is assumed that both runoff from offsite onto the site and runoff from the site to an offsite location are prevented by ditching, diking or other means. Therefore, runoff is limited to that occurring in the specified field area.

In the computer model, pathogens in runoff water are considered separately from those associated with suspended sediments. The concentration of pathogens in runoff water depends on how readily they are separated from the soil particles and how well they remain in suspension. Viral particles may be tightly bound to soil particles and thus be difficult to suspend in runoff water, but suspended viruses do not readily settle out of suspension because they are so small. In contrast, parasite ova, cysts and oocysts are less tightly bound by soil particles, but their large size makes them settle out of suspension rapidly.

It is assumed that organisms in the top 1 cm of soil are available for suspension in runoff water after a rainfall. The fraction of total rainfall occurring as runoff is calculated by Subroutine RAINS, and the fraction of organisms in the soil surface that are suspended in runoff water is given in the model by the variable SUSPND [P(45)]. Although there have been several studies on suspension of soil-associated viruses and bacteria, there are few data describing the suspension of parasites in runoff water. In the model it is assumed that the fraction of parasites suspended is 0.01 in Practice I, in which the soil surface has little cover, and 0 in Practices II and III, in which the soil has a continuous grass surface.

3.4.3. Transport by Wind. The ability of protozoan cysts and *Cryptosporidium* oocysts to survive in aerosols has not been determined. However, Lawande and associates (1979) recovered soil amebae, transmitted by the dust-laden air during the harmattan period, from the nasal passages of children in Nigeria. Of the 50 children evaluated, 24% had positive cultures for the soil amebae. The pathogenic strains of *Naegleria fowleri* recovered from two children were viable and infective, killing mice in five days.

Rivera et al. (1987) have also isolated airborne, free-living amebae from the atmosphere of Mexico City. The authors suggest that the ability of the cyst-forming amebae to exist and remain viable in the atmosphere can, under favorable environmental conditions, contribute to dispersion and invasion of water supplies, food, or healthy people.

Airborne transport of dry larvae or eggs of nematodes has been modeled by Carroll and Viglierchio (1981) using simplified Gaussian plume models. They measured the sedimentation velocities of dry larval, egg and cyst forms of a number of parasites and found that most fell between 0.1 and 0.6 m/sec, indicating that they would be more erodible than dry soil particles. Their results indicated that, given the presence of eggs or larvae on a loose, dry soil surface and with sufficient wind velocity (11 m/sec, particles lofted to a height of 30 m by tilling), eggs could be carried up to 0.6 km and larval forms 1-3 km as a result of tilling. The authors concluded that nearly all dust suspended by wind vortices (dust devils) would be deposited within 4 km, but a few individual organisms could be transported as far as 40 km away.

The authors' calculations indicated that the maximum concentration (pathogens/m^3) of larval forms at a distance of 80 m during cultivation at a windspeed of 2 m/sec was approximately 4% of the release rate (in pathogens/sec). The U.S. EPA model for tilling emissions (U.S. EPA, 1983) yields a release rate of approximately 1.06 kg soil/hr, or approximately 0.3 g/sec. At a sludge application rate of 10 T/ha, a concentration of 5000 pathogens/kg, and dispersal of the pathogens in 2x10^{6} kg surface soil/ha (Naylor and Loehr, 1982), the concentration of pathogens in soil would be 0.025 pathogens/g. Thus the concentration of pathogens transported 80 m by wind in the case described above would be 0.04x0.3x0.025=3x10^{-4} pathogens/m^{3}. This figure implies a low risk of infection by windblown pathogens as a result of tilling and subsequent air transport.

4. PARAMETERS FOR MODEL RUNS

4.1. RATIONALE FOR PARAMETER SELECTION

The assessment of human health risk from pathogenic parasites as a result of land application of sewage sludge requires a realistic description of the fate and transport of the pathogens. Information in the published literature confirms that protozoan cysts and parasite ova survive during the sewage treatment process, but quantitative data on survival of protozoa in sludge are scarce. There appear to be few quantitative measures of movement or die-off rates of ova or cysts in soil or their inclusion in aerosols. Most researchers assume that ova and cysts are too large to migrate in soil or into groundwater. That assumption was maintained in this analysis. Some researchers conclude that ova and cysts are unlikely to be included in droplet aerosols. In this analysis, however, it was assumed that ova and cysts would be included in any droplet aerosols formed by spray application, as well as in any particulate aerosols formed as a result of disturbance of the soil by wind or cultivation. Although the droplet aerosol model includes droplets smaller than ova and cysts, no modifications were made to exclude these particles from the infectiveness calculation. Therefore, estimates of the infectiveness of very small droplets may be unrealistically high.

Various estimates have been made for the rates of inactivation of parasite ova and protozoan cysts. These forms of the pathogens are more resistant to environmental conditions than the unencysted, larval or adult forms, which do not survive sewage treatment. Therefore, ova and cysts are considered to be more significant with regard to exposure risk from sewage sludge. However, the survival properties of ova and cysts depend on the specific organism in question, as well as on the conditions to which they are exposed. Therefore, a single mathematical description of die-off will at best only approximate the behavior of all parasites. Default values in the model for die-off of ova and cysts are those found in the initial version of the model (U.S. EPA, 1980). They are:

During application/incorporation
    0 for Temp $< 20°C$;
    $10^{(-0.000178)}$ or 0.00041/hour for $20 \leq$ Temp < 40;
    $10^{(-0.456)}$ or 0.65/hour for Temp ≥ 40;

In moist soil

0 for Temp < 20°C or for 8 hours after irrigation;
$10^{(-0.00023)}$ or 0.000533/hour for $20 \leq \text{Temp} < 40$;
$10^{(-0.667)}$ or 0.7845/hour for $40 \leq \text{Temp} \leq 50$;
$10^{(-0.125)}$ or 0.25/hour for $\text{Temp} > 50$;

On crop surfaces

$10^{(-0.667)}$ or 0.7845/hour at all temperatures;

In water

$10^{(-0.00023)}$ or 0.000533/hour at all temperatures.

A 90% die-off time of 270 days for Ascaris ova in soil reported by Sorber and Moore (1986) implies an exponential rate of $10^{(-1/270*24)}$ or $10^{(-0.000154)}$/hour (fractional rate 0.00035/hour); this value is near the model's default value. In the model analysis a value of $10^{(-0.0001)}$/hour was used as a lower limit for die-off rate in moist soil.

O'Donnell et al. (1984) reported a decrease in the number of recoverable Ascaris ova treated in sludge and stored in soil. The decrease occurred at rates of approximately $10^{(-0.2)}$/month for aerobically treated sludge and approximately $10^{(-0.3)}$/month for anaerobically treated sludge; viability of the ova recovered dropped at a rate of $\sim 10^{(-0.005)}$/month for aerobically treated sludge and $10^{(-0.095)}$/month for anaerobically treated sludge, giving composite rates for Ascaris of $10^{(-0.205)}$/month ($10^{(-0.00023)}$/hour) for aerobically treated sludge and $10^{(-0.395)}$/month ($10^{(-0.00045)}$/hour) for anaerobically treated sludge. The value for aerobically treated sludge agrees well with the default value. A value of $10^{(-0.0005)}$/hour was used as an upper limit for the model analysis. Recovery and viability of Toxocara, Trichuris and Hymenolepis ova appeared not to be greater than for Ascaris (O'Donnell et al., 1984).

Published data on die-off rates for parasites in sludge are summarized in Table 4-1. For maximum utility, rates should be determined for all of the organisms listed. However, quantitative data are not available for most of them.

TABLE 4-1

DIE-OFF RATES OF PARASITES IN SLUDGE

Pathogen	Die-Off rate (log die-off/hour)				References
	Moist Soil (20-40° C)	Dry Particulate	Water	Droplet Aerosol	
HELMINTHS - Nematoda					
Ancylostoma duodenale					
Ancylostoma braziliense					
Ancylostoma caninum					
Ascaris lumbricoides	-0.000154 to -0.00138				Sorber and Moore, 1986
Ascaris suum					
Enterobius vermicularis					
Necator americanus					
Strongyloides stercoralis					
Toxocara canis					
Toxocara cati					

TABLE 4-1

DIE-OFF RATES OF PARASITES IN SLUDGE (continued)

Pathogen	Die-Off rate (log die-off/hour)				References
	Moist Soil (20-40° C)	Dry Particulate	Water	Droplet Aerosol	
HELMINTHS - Nematoda (continued)					
Trichuris trichiura					
HELMINTHS - Cestoda					
Echinococcus multilocularis					
Hymenolepis nana					
Taenia saginata					
Taenia solium					
PROTOZOA					
Balantidium colic					
Cryptosporidium parvum					
Dientamoeba fragilis					
Entamoeba histolytica					
Giardia lamblia					
Isospora belli					
Isospora hominis					
Toxoplasma gondii					

4.2. PARAMETER VALUES

Prior to the site-specific simulations, an initial sensitivity analysis was performed. In this analysis, several parameters were systematically varied to simulate a variety of possible conditions, application methods and agricultural practices. The parameters varied included those of the main program, Subroutine RISK and Subroutine RAINS. The ranges of values and rationale for their selection are discussed below.

4.2.1. Main Program Parameters. The main program parameters varied for this analysis are listed below (default values are in **bold-face** type):

VARIABLE # NAME	VALUES	DEFINITION AND RATIONALE FOR VALUES
1 ASCRS	200 **5000** 11000	Concentration of organisms in sludge (number/kg dry wt). Values as high as 11,000/kg have been reported (Wallis et al., 1984), and values less than the default have been reported.
2 APRATE	**1.0×10^4** 2.5×10^4	Rate of application of sludge (kg/ha). Demonstrate the effect of increased sludge concentration in soil.
4 TREG	0	Waiting period before harvesting (months). Make parasites available immediately for exposure as a worst case.
6 APMETH	-1 0 +1	Application method (flag). Demonstrate the relative effects of spray application, surface application, and subsurface application.
13 TRAIN	Site-specific	Flag for rainfall subroutine menu. Rainfall is the most significant factor in surface runoff/sediment transport to the onsite pond.
17 IRMETH	**0** 1	Irrigation method (flag). Compare the effects of spray irrigation and ditch irrigation.
18 DILIRR	**0** 1	Fraction of irrigation water that is contaminated. Demonstrate the effect of irrigation with sludge as compared to uncontaminated water.

VARIABLE # NAME	VALUES	DEFINITION AND RATIONALE FOR VALUES
30 COVER	**0** 0.9	Percent of ground surface covered by vegetation. Compare surface runoff/sediment transport for bare soil and soil with vegetation (will be matched with values in Subroutine RAINS).
31 AEREFF	**1×10^{-3}** 2×10^{-2}	Efficiency of aerosol formation. Compare default value to an unrealistically high value to determine whether the model is sensitive to offsite aerosols.
45 SUSPND	**0.01** 0.001	Fraction of soil surface organisms suspended in soil surface water. Vary to determine whether model is sensitive to resuspension from surface soil into soil surface water.
59 DTCTMT	0 1	Fraction of pathogens ingested by animals that is transferred to meat. No transfer of parasites to meat [P(59)=0], or invasion of edible tissue by every infective ovum or cyst [P(59)=1].
60 DTCTMK	0 1	Fraction of pathogens ingested by animals that is transferred to milk. No transfer of parasites to milk [P(60)=0], or invasion of milk by every infective cyst [P(60)=1].
66 CROP	-1 0 +1	Type of crop (flag). Type of crop is important in exposure during consumption of crop.
67 TCULT	0 -2	Cultivation time (hr) or flag. Include regular cultivation to determine whether model is sensitive to generation of particulate aerosols.
68 TCROP	240	Time crop surface is present (hr). Establish early appearance of crop surface to facilitate demonstration of sensitivity of exposure to presence of crop.
69 THARV	300	Harvest time (hr). Establish early harvesting of crop to facilitate demonstration of sensitivity of exposure to presence of crop.

The variable DTCTMT [P(59)] is used to describe the transfer of parasites from contaminated soil or feed to meat. This process accounts for ingestion of infective ova or larvae by livestock, with subsequent migration of larvae to edible tissues. Upon ingestion of meat containing cysts, infection of the food consumer (EATER) would occur. In all other exposure pathways, it is assumed that the EATER ingests infective ova or larvae.

4.2.2. Parameters for Subroutine RISK. Parameters varied for Subroutine RISK are listed below (default values are in **bold-face** type):

PARAMETER # NAME	VALUE	DEFINITION AND RATIONALE FOR CHOICE OF VALUES
5 DRECTC	0.1 0.02	Ingestion of crop surface (g/day). Determine effect of reducing ingestion of contaminated crop surface during routine daily work in the field.
6 DRECTS	**0.1** 0.02 0.2	Ingestion of or direct contact with soil (g/day). Determine effects of reducing ingestion of contaminated soil during routine daily work and of including transdermal invasion from soil on the skin surface.
34. XDIST	**200** 100	Distance (m) downwind of receptor from particulate source. Determine effects of reducing distance to receptor of offsite aerosol to verify initial indications that offsite exposure is negligible.

DRECTS (Variable 6) is intended to represent infection by direct contact with contaminated soil or crop surfaces. This exposure pathway includes both transdermal invasion by parasites and inadvertent ingestion of infective forms. The default value (0.1 g/day) was chosen to be conservative in comparison to U.S. EPA estimates of ingestion of dust and soil by adults (0.02 g/day; U.S. EPA, 1983). Typical rates of soil ingestion by children are higher, with a 95th percentile value of 0.4-0.6g/day (Binder et al., 1986). The U.S. EPA suggests a daily intake of 0.2 g/day for children under 5 for assessment of risk from toxic chemicals (U.S. EPA, 1990a). However, children (and adults) with pica, a behavior characterized by intentional ingestion of soil or other mineral substances, may ingest much larger amounts of soil. For example, Calabrese (1988) reports ingestion of 5-8 g soil/day by one subject. For these persons, the risk of infection from contaminated soil is much greater than for the general population. To model risk of infection to persons exhibiting pica, any chosen value can be used for DRECTS during the input phase of the model run. Exposure by ingestion of or direct contact with contaminated soil or crop surfaces is summed with aerosol exposures to calculate the probability of infection ONSITE.

4.2.3. Subroutine GRDWTR. Because it was assumed that parasite ova and protozoan cysts are not transported into groundwater, this subroutine was not used in the model test runs. However, since protozoan cysts are small (5-25 μm), their migration through porous soil may not be completely prevented. If the user wished to model subsurface transport in groundwater, appropriate values for parasites would be entered during the input phase of a model run using the bacteria or virus option of the model. However, data on such parameters as retardation coefficient and hydrodynamic dispersion coefficient have not been found.

4.2.4. Subroutine RAINS. The Modified Universal Soil Loss Equation, which is the basis for Subroutine RAINS, depends on soil type, topography and land-use practices, so parameters for Subroutine RAINS are influenced strongly by the choice of site. A variety of locations representing different soil types, topography and climate were selected as test sites for model runs. Values for the parameters in Subroutine RAINS were chosen to be appropriate for soil type, topography and meteorological patterns for the chosen locations. Although the model is limited in its ability to represent the rainfall pattern of any location because of its restriction to no more than ten rainfall events, these events were included as early in the model run as possible to ensure that the effects of rainfall on surface runoff/sediment transport were maximized.

Subroutine RAINS is described in more detail in U.S. EPA (1990b). Parameters used by Subroutine RAINS include the following:

PARAMETER		DEFINITION
#	NAME	
2	PDUR	Event-specific duration of rainfall (hours)
3	PTOT	Event-specific amount of rainfall (cm)
4	BTLAG	Basin time lag. Depends on site-specific properties.
5	CN	Curve number. Depends on site-specific properties.
6	AMC	Antecedent moisture conditions (dry, intermediate or wet)
7	STAD	Event-specific storm advancement coefficient
8	USLEK	USLE K factor (soil erodibility)
9	USLEL	USLE L factor (from length of slope)
10	USLES	USLE S factor (from steepness of slope)
11	USLEC	USLE C factor (cover management)

Values used for these variables in the model runs are given in Section 5 along with the site descriptions.

Since Practices IV and V do not include an onsite pond to receive surface water runoff, parameters for Subroutine RAINS are given only for Practices I, II and III.

5. SITES FOR MODEL RUNS

Six sites were chosen to provide a variety of soil types, topography and meteorological patterns. Other than Anderson County, TN, for which more detailed meteorological data were available to the authors, specific sites were chosen arbitrarily with the goal of geographic diversity. Data on soil properties were taken from U.S. Soil Conservation Service soil surveys, which have been developed for each county in the United States. Meteorological data were taken from the National Oceanic and Atmospheric Administration Local Climatological Data Annual Summaries for 1981 (NOAA, 1981). The sites chosen for the model runs are described below.

5.1. SITE 1: ANDERSON COUNTY, TENNESSEE

Values of site-specific variables were chosen to reflect conditions at an agricultural location in the Clinch River Valley of East Tennessee.

5.1.1. Description of Soil. The soil chosen for the model run is the Claiborne series, which comprises fine-loamy, siliceous, mesic Typic Paleudults. It is further described as follows (USDA, 1981a):

> The Claiborne series consists of deep, well drained soils that formed in sediment deposited by water or in residuum of dolomite. These soils are on ridgetops, on hillsides, and at the base of slopes. The slope range is 5 to 45 percent, but in most areas the gradient is 12 to 30 percent....
>
> The solum is more than 60 inches thick. Depth to dolomite bedrock is more than 72 inches. The soil is strongly acid or very strongly acid throughout except for the surface layer where limed. The content of coarse chert fragments ranges form 5 to 25 percent in each horizon. These fragments commonly increase in size and abundance with increasing depth.

Claiborne soils are of hydrologic group B, characterized by moderately low runoff potential, moderate infiltration rates and moderate rates of water transmission.

For this analysis, it was assumed that sites with slopes greater than 10% (6°) would not be used because of the likelihood of excessive runoff.

5.1.2. Narrative Climatological Summary. The following climatological summary for Oak Ridge, Anderson County, TN, was taken from NOAA (1981):

> Oak Ridge is located in a broad valley between the Cumberland Mountains, which lie to the northwest of the area, and the Great Smoky Mountains, to the southeast. These mountain ranges are oriented northeast-southwest and the valley between is corrugated by broken ridges 300 to 500 feet high and

oriented parallel to the main valley. The local climate is noticeably influenced by topography. Prevailing winds are usually either up-valley, from west to southwest, or down-valley, from east to northeast. During periods of light winds daytime winds are usually southwesterly, nighttime winds usually northeasterly. Wind velocities are somewhat decreased by the mountains and ridges. Tornadoes rarely occur in the valley between the Cumberlands and the Great Smokies. In winter the Cumberland Mountains have a moderating influence on the local climate by retarding the flow of cold air from the north and west.

The coldest month is normally January but differences between the mean temperatures of the three winter months of December, January, and February are comparatively small. The lowest mean monthly temperature of the winter has occurred in each of the months December, January, or February in different years. The lowest temperature recorded during the year has occurred in each of the months November, December, January, or February in various years. July is usually the hottest month but differences between the mean temperatures of the summary months of June, July, and August are also relatively small. The highest mean monthly temperature may occur in either of the months June, July, or August and the highest temperature of the year has occurred in the months of June, July, August, and September in different years. Mean temperatures of the spring and fall months progress orderly from cooler to warmer and warmer to cooler, respectively, without a secondary maximum or minimum. Temperatures of 100° [38°C] or higher are unusual, having occurred during less than one-half of the years of the period of record, and temperatures of zero or below are rare. The average number of days between the last freeze of spring and the first freeze of fall is approximately 200. The average daily temperature range is about 22° [12°C] with the greatest average range in spring and fall and the smallest in winter. Summery nights are seldom oppressively hot and humid. Low level temperature inversions occur during approximately 57 percent of the hourly observations. Fall is usually the season with the greatest number of hours of low level inversion with the number decreasing progressively through spring and winter to a summertime minimum but seasonal differences are small.

5.1.3. Temperature. The monthly average temperatures at this location ranged between a low of 2.8° C and a high of 24.8° C.

5.1.4. Rainfall. An hourly rainfall record for April and May, 1989, was obtained from the Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, TN. Profiles of the first ten rain events beginning April 1, the time the model run is initiated, were constructed from this record. Profiles consisted of the duration of the event (PDUR), the total amount of precipitation in the event (PTOT) and the storm advancement coefficient (STAD), which was determined by inspection of the hourly precipitation. The resulting parameters were as follows:

Event No.	START (hr)	PDUR (hr)	PTOT	STAD (cm)
1	77	5	1.60	0.65
2	174	8	1.52	0.36
3	726	11	1.55	0.12
4	826	7	3.30	0.27
5	924	4	1.50	0.56
6	1180	5	2.31	0.19
7	1340	12	4.06	0.52
8	1549	2	1.63	0.46
9	1590	9	2.52	0.52
10	1650	14	3.48	0.45

5.1.5. **Parameters for Subroutine RAINS.** Parameters for Subroutine RAINS were modified to describe local rainfall and soil conditions for Anderson County, TN. Values were calculated as described in Appendix B of U.S. EPA (1990b). The values used in the model run were based on a field with dimensions 500 m by 200 m, sloping at an angle of 6° (10.5%). It was assumed for Practice I that before a crop was present, the cover management factor was not modified, whereas after the crop was present, a canopy cover of 30%, a canopy height of 0.5 m and a relative root network factor of 30% were provided; for Practices II and III, the canopy cover was taken to be 90%, the canopy height was taken to be less than 0.5 m and a relative root network factor of 90% was assumed. The resulting values were:

Parameter		PRACTICE NUMBER		
No.	Name	I	II	III
4	BTLAG	0.2	0.31	0.31
5	CN	78	64	64
6	AMC	3 (<TCROP) 2 (≥TCROP)	2	2
8	USLEK	0.32	0.32	0.32
9	USLEL	4.76	4.76	4.76
10	USLES	1.25	1.25	1.25
11	USLEC	0.45 (<TCROP) 0.30 (≥TCROP)	0.02	0.02

The initial value (0.02) for USLEC in Practices II and III was subsequently shown to cause errors which halted operation of the program, so in subsequent runs and for all other sites that parameter value was changed to 0.05.

5.2. SITE 2: CHAVES COUNTY, NEW MEXICO

Values for site-specific variables for Site 2 were chosen to represent an agricultural area near Roswell, a city in southeast New Mexico.

5.2.1. Description of Soil. The soil chosen for the model run is the Pecos Series, which comprises fine, mixed, thermic Torrertic Haplustolls. It is further described as follows (USDA, 1980):

> The Pecos series are deep, moderately well drained, very slowly permeable soils on flood plains. The soils formed in calcareous, saline, stratified, clayey alluvium. Slope is 0 to 1 percent.
>
> Typically, the surface layer is reddish brown silty clay loam about 12 inches thick. The upper 10 inches of the substratum is reddish brown clay, the next 20 inches is reddish brown silty clay and silty clay loam, and the lower part to a depth of 60 inches or more is brown loam and fine sandy loam. Salinity is moderate. Available water capacity is high.

Pecos soils are of hydrologic group D, characterized by having a very slow infiltration rate (high runoff potential) when thoroughly wet. They consist chiefly of clays that have a high shrink-swell potential, soils that have a permanent high water table, soils that have a claypan or clay layer at or near the surface, and soils that are shallow over nearly impervious material. These soils have a very slow rate of water transmission.

5.2.2. Narrative Climatological Summary (NOAA, 1981).

> The climate at Roswell conforms to the basic trend of the four seasons, but shows certain deviations related to geography. A location south and west of the main part of major weather activity affords a degree of climatic seclusion. There are also topographic effects that are inclined to alter the course of the weather in this area. Higher landmasses almost surround the valley location, with a long, gradual descent from points southwest through west and north. The topography acts to modify air masses, especially the cold outbreaks in wintertime. Downslope warming of air, as well as air interchange within a tempering environment, often prevents sharp cooling. Moreover, the elevation of 3,600 feet in common with the geographic situation, discourages a significant part of the heat and humidity that originates in the south in summer. In winter, subfreezing at night is tempered by considerable warming during the day. Zero [°F] or lower temperatures occur as a rule a time or two each winter. Subzero cold spells are of short duration. Winter is the season of least precipitation.

5.2.3. Temperature. The monthly average temperatures at this location ranged between a low of 4.2° C and a high of 26.2° C.

5.2.4. **Rainfall.** Times, duration and total rainfall for each rainfall event were constructed from the rainfall record for 1980 at the location (NOAA, 1981). The record provided the date and amount of the largest rainfall during a 24-hour period each month, as well as the total amount of rainfall each month. The largest rainfall (greater than the subroutine's lower limit of 1 cm) was always used, and the remaining rainfall during the period was divided into events placed at arbitrary times. The storm advancement coefficient was chosen to reflect the nature of rainfall in the region; the low number used reflects a preponderance of thunderstorms and sudden showers, whereas larger numbers were used for some other sites to reflect a more gradual buildup of the rainstorm. The resulting parameters were as follows:

Event No.	START (hr)	PDUR (hr)	PTOT (cm)
1	328	5	1.17
2	784	8	4.5
3	966	6	4.55
4	1280	3	1.5
5	1830	8	3.05
6	2174	10	7.75
7	2366	10	12.47
8	2800	5	3.45
9	3328	10	4.19
10	3518	6	3.0

5.2.5. **Parameters for Subroutine RAINS.** Parameters for Subroutine RAINS were modified to describe local rainfall and soil conditions. The slope value used in the model run was 1 degree (1.7%). The resulting values were:

Parameter		PRACTICE NUMBER		
No.	Name	I	II	III
4	BTLAG	0.32	0.38	0.38
5	CN	89	84	84
7	STAD	0.25	0.25	0.25
8	USLEK	0.32	0.32	0.32
9	USLEL	2.54	2.54	2.54
10	USLES	0.16	0.16	0.16
11	USLEC	0.45 (<TCROP) 0.25 (≥TCROP)	0.05	0.05

5.3. SITE 3: CLINTON COUNTY, IOWA

Values for site-specific variables for site 3 were chosen to represent an agricultural area in eastern Iowa in a county that borders on the Mississippi River.

5.3.1. Description of Soil. The soil chosen for the model run is the Fayette Series, which comprises fine-silty, mixed, mesic type Hapludalfs. It is further described as follows (USDA, 1981b):

> The Fayette series consists of well drained, moderately permeable soils on loess-covered uplands. These soils formed in loess that is more than 40 inches thick. Slope ranges from 2 to 40 percent.
>
> The solum ranges from 40 to 60 inches in thickness. There are no carbonates to a depth of 40 inches to 60 inches.

Fayette soils are of hydrologic group B, characterized by moderately low runoff potential, moderate infiltration rates, and moderate rates of water transmission.

5.3.2. Narrative Climatological Summary. Because a meteorological report for Clinton County was not included in NOAA (1981), the climatological summary and data reported for nearby Dubuque, IA, (NOAA, 1981) were used:

> The principal feature of the climate in Dubuque is its variety. Standing, as it does, at the crossroads of the various air masses that cross the continent, the Dubuque area is subject to weather ranging from that of the cold, dry, arctic air masses in the winter with readings as low as 32° below [-36°C], when the ground is snow covered, to the hot, dry weather of the air masses from the desert southwest in the summer when the temperatures reach as high as 110° [43°C]. More often the area is covered by mild Pacific air that has lost considerable moisture in crossing the mountains far to the west, or by cool, dry Canadian air, or by warm, moist air from the Gulf regions. Most of the year the latter three types of air masses dominate Dubuque weather, with the invasions of Gulf air rarely occurring in the winter.
>
> The seasons vary widely from year to year at Dubuque; for example, successive invasions of cold air from the north may just reach this far one winter and bring a long, cold winter with snow-covered ground from mid-November until March, and many days of sub-zero temperatures, while another season the cold air may not reach quite this far and the winter can be mild with bare ground most of the season, and only a few sub-zero readings. The summers, too, may vary from hot and humid with considerable thunderstorm activity when the Gulf air prevails, to relatively cool, dry weather when air of northerly origin dominates the season.

5.3.3. Temperature. The monthly average temperatures at this location ranged between a low of -7.5° C and a high of 23.2° C.

5.3.4. Rainfall. Times, duration and total rainfall for each rainfall event were constructed from the rainfall record for 1980 (NOAA, 1981). The resulting rainfall parameters were as follows:

Event No.	START (hr)	PDUR (hr)	PTOT (cm)
1	180	8	2.84
2	231	6	1.0
3	396	8	1.6
4	636	6	1.2
5	970	6	1.0
6	1264	8	1.27
7	1791	10	6.12
8	1834	10	4.56
9	1934	6	3.0
10	2080	4	2.5

5.3.5. Parameters for Subroutine RAINS. Parameters for Subroutine RAINS were modified to describe soil conditions for Clinton County, IA, and rainfall for Dubuque, IA, the nearest reporting station. The slope value used in the model run was 4.6° (8%). The resulting values were:

Parameter		PRACTICE NUMBER		
No.	Name	I	II	III
4	BTLAG	0.17	0.26	0.26
5	CN	78	61	61
6	AMC	3 (<TCROP) 2 (≥TCROP)	2	2
7	STAD	0.375	0.375	0.375
8	USLEK	0.37	0.37	0.37
9	USLEL	4.76	4.76	4.76
10	USLES	0.85	0.85	0.85
11	USLEC	0.45 (<TCROP) 0.30 (≥TCROP)	0.05	0.05

5.4. SITE 4: HIGHLANDS COUNTY, FLORIDA

Values for site-specific variables for Site 4 were chosen to represent a sandy soil in central Florida. These soils can be productive for agriculture but can be improved greatly by amendment.

5.4.1. **Description of Soil.** The soil chosen for the model run is the Archbold Series, which comprises hyperthermic, uncoated Typic Quartzipsomments. It is further described as follows (USDA, 1989):

> The Archbold series consists of nearly level to gently sloping, moderately well drained, droughty soils that formed in marine and eolian deposits. These soils are on moderately high ridges in the ridge part of the county. The slopes range from 0 to 5 percent.
>
> Typically, the surface layer is gray sand about 4 inches thick. The underlying material to a depth of 80 inches or more is white sand.
>
> The soil reaction is slightly acid to extremely acid. The texture is sand or fine sand. The content of silt plus clay in the 10- to 40-inch control section is less than 2 percent.

Archbold soils are of hydrologic group A, characterized by having a high infiltration rate (low runoff potential) when thoroughly wet. They consist mainly of deep, well drained to excessively drained sands or gravelly sands. These soils have a high rate of water transmission.

5.4.2. **Narrative Climatological Summary.** Because meteorological information was not given in NOAA, 1981 for Highlands County, the summary and data for nearby Orlando, FL, were used.

> Orlando, by virtue of its location in the central section of the Florida peninsula (which is abounding with lakes), is almost surrounded by water and, therefore, relative humidities remain high here the year round, with values hovering near 90 percent at night and dipping to 40 to 50 percent in the afternoon (sometimes to 20 percent in the winter).
>
> The rainy season extends from June through September (sometimes through October when tropical storms are near). During this period, scattered afternoon thundershowers are an almost daily occurrence, and these bring a drop in temperature to make the climate bearable (although, most summers, temperatures above 95° [35°C] are rather rare). Too, a breeze is usually present, and this also contributes towards general comfort.

5.4.3. **Temperature.** The monthly average temperatures at this location ranged between a low of 15.8° C and a high of 28.0° C.

5.4.4. **Rainfall.** Times, duration and total rainfall for each rainfall event were constructed from the rainfall record for 1980 at Orlando (NOAA, 1981). The resulting parameters were as follows:

Event No.	START (hr)	PDU (hr)	PTOT (cm)
1	1043	7	2.1
2	1166	8	3.12
3	1667	10	11.17
4	1789	9	5.7
5	1958	6	3.0
6	2536	10	3.17
7	2918	6	2.0
8	3301	6	1.6
9	3547	7	2.44
10	4025	10	9.93

In model runs from Practice I, Subroutine RAINS returned a floating-point error during computations for rainfall event 9. This error did not occur for Practices II and III, so it was probably related to both the number of organisms and the long time over which the subroutine operated. In order to complete the model run, it was necessary to delete rainfall events 9 and 10 for Practice I.

5.4.5. **Parameters for Subroutine RAINS.** Parameters for Subroutine RAINS were modified to describe local rainfall reported for Orlando, FL, and soil conditions for Highlands County, FL. The slope value used in the model run was 1.2° (2%). The resulting values were:

Parameter		PRACTICE NUMBER		
No.	Name	I	II	III
4	BTLAG	0.45	0.8	0.8
5	CN	67	39	39
7	STAD	0.2	0.2	0.2
8	USLEK	0.1	0.1	0.1
9	USLEL	2.54	2.54	2.54
10	USLES	0.26	0.26	0.26
11	USLEC	0.45 (<TCROP) 0.25 (≥TCROP)	0.05	0.05

5.5. SITE 5: KERN COUNTY, CALIFORNIA

Values for site-specific variables for Site 5 were chosen to represent a soil near Bakersfield, CA, which is located in southern California.

5.5.1. Description of Soil. The soil chosen for the model run is the Arvin series, which comprises coarse-loamy, mixed, nonacid, thermic Mollic Xerofluvents. It is further described as follows (USDA, 1981c):

> The Arvin series consist of very deep, well drained soils on alluvial fan, stream flood plains, and stream terraces. These soils formed in mixed alluvium derived from granitic rock. Slope ranges from 2 to 9 percent.
>
> Clay content ranges from 5 to 18 percent in the control section. Organic matter content is 0.9 percent or less. Reaction is slightly acid to mildly alkaline throughout.

Arvin soils are of hydrologic group B, characterized by moderately low runoff potential, moderate infiltration rates and moderate rates of water transmission.

5.5.2. Narrative Climatological Summary (NOAA, 1981).

> Bakersfield, situated in the extreme south end of the great San Joaquin Valley, is partially surrounded by a horseshoe-shaped rim of mountains with an open side to the northwest and the crest at an average distance of 40 miles.
>
> The Sierra Nevadas to the northeast shut out most of the cold air that flows southward over the continent during winter. They also catch and store snow, which provides irrigation water for use during the dry months. The Tehachapi Mountains, forming the southern boundary, act as an obstruction to northwest wind, causing heavier precipitation on the windward slopes, high wind velocity over the ridges and, at times, prevailing cloudiness in the south end of the valley after skies have cleared elsewhere. To the west are the coast ranges, and the ocean shore lies at a distance of 75 to 100 miles.
>
> Because of the nature of the surrounding topography, there are large climatic variations within relatively short distances. These zones of variation may be classified as Valley, Mountain, and Desert areas. The overall climate, however, is warm and semi-arid. There is only one wet season during the year, as 90 percent of all precipitation falls from October thorough April, inclusive. Snow in the valley is infrequent, with only a trace occurring in about one year out of seven. Thunderstorms also seldom occur in the valley.

5.5.3. Temperature. The monthly average temperatures at this location ranged between a low of 8.5° C and a high of 28.8° C.

5.5.4. **Rainfall.** Times, duration and total rainfall for each rainfall event were constructed from the rainfall record for 1980 at the location (NOAA, 1981). The resulting parameters were as follows:

Event No.	START (hr)	PDUR (hr)	PTOT (cm)
1	16	8	1.0
2	4378	10	1.78
3	7256	9	1.47
4	7530	6	1.07
5	8016	6	1.0
6	8320	5	1.0
7	8606	8	1.63
8	8782	8	1.0
9	13164	10	1.78
10	16022	9	1.47

5.5.5. **Parameters for Subroutine RAINS.** Parameters for Subroutine RAINS were modified to describe local rainfall and soil conditions. The slope value used in the model run was 1.7° (3%). The resulting values were:

Parameter No.	Name	PRACTICE NUMBER I	II	III
4	BTLAG	0.3	0.45	0.45
5	CN	78	61	61
6	AMC	3 (<TCROP) 2 (≥TCROP)	2	2
8	USLEK	0.32	0.32	0.32
9	USLEL	2.54	2.54	2.54
10	USLES	0.26	0.26	0.26
11	USLEC	0.45 (<TCROP) 0.25 (≥TCROP)	0.05	0.05

5.6. SITE 6: YAKIMA COUNTY, WASHINGTON

Values for site-specific variables for Site 6 were chosen to represent a soil near Yakima, WA, which is located in south-central Washington along the Yakima River. This is a region of fairly low rainfall, but which is successfully farmed by irrigation.

5.6.1. **Description of Soil.** The soil chosen for the model run is the Kittitas Series, which comprises fine-silty, mixed (calcareous), mesic Fluvaquentic Haplaquolls. It is further described as follows (USDA, 1985):

> The Kittitas series consists of very deep, somewhat poorly drained soils on flood plains. These soils formed in mixed alluvium. Slopes range from 0 to 2 percent.

Kittitas soils are of hydrologic group C, characterized by a slow infiltration rate when thoroughly wet. They consist chiefly of soils having a layer that impedes the downward movement of water or soils of moderately fine texture or fine texture. These soils have a slow rate of water transmission.

5.6.2. Narrative Climatological Summary (NOAA, 1981).

> Yakima is located in a small east-west valley in the upper (northwestern) part of the irrigated Yakima Valley. Local topography is complex with a number of minor valleys and ridges giving a local relief of as much as 500 feet. This complex topography results in marked variations in air drainage, winds, and minimum temperatures within short distances.
>
> The climate of the Yakima Valley is relatively mild and dry. It has characteristics of both maritime and continental climates, modified by the Cascade and the Rocky Mountains, respectively. Summers are dry and rather hot, and winters cool with only light snowfall. The maritime influence is strongest in winter when the prevailing westerlies are the strongest and most steady. The Selkirk and Rocky Mountains in British Columbia and Idaho shield the area from most of the very cold air masses that sweep down from Canada into the Great Plains and eastern United States. Sometimes a strong polar high pressure area over western Canada will occur at the same time that a low pressure area covers the southwestern United States. On these occasions, the cold arctic air will pour through the passes and down the river valleys of British Columbia, bringing very cold temperatures to Yakima. That this happens infrequently is shown by the occurrence of temperatures of 0 degrees [F] or below on only 4 days a winter on the average. On about 21 days during the winter the temperature will fail to rise to the freezing point. In January and February 1950, there were 4 consecutive days colder than -20° [-29°C], including -25° [-32°C] on February 1. However, over one-half of the winters remain above 0 degrees [F (-18°C)].

5.6.3. Temperature. The monthly average temperatures at this location ranged between a low of -1.5° C and a high of 22.3° C.

5.6.4. Rainfall. Times, duration and total rainfall for each rainfall event were constructed from the rainfall record for 1980 at the location (NOAA, 1981). The resulting parameters were:

Event No.	START (hr)	PDUR (hr)	PTOT (cm)
1	1628	6	1.0
2	4290	8	1.25
3	4506	10	2.06
4	5490	6	1.14
5	5722	6	1.0
6	5966	6	1.0
7	7002	10	2.65
8	7212	8	1.5
9	7498	8	1.2
10	7816	8	1.0

5.6.5. **Parameters for Subroutine RAINS.** Parameters for Subroutine RAINS were modified to describe local rainfall and soil conditions. The slope value used in the model run was 0.6° (1%). The resulting values were:

Parameter No.	Name	PRACTICE NUMBER I	II	III
4	BTLAG	0.4	0.5	0.5
5	CN	85	74	74
8	USLEK	0.43	0.43	0.43
9	USLEL	2.54	2.54	2.54
10	USLES	0.12	0.12	0.12
11	USLEC	0.45 (<TCROP) 0.25 (≥TCROP)	0.05	0.05

6. RESULTS

6.1. SENSITIVITY TO VARIABLES

Limitations in mathematical processes and in the computer's operating system result in calculated probabilities of infection that, strictly speaking, are approximations rather than accurate evaluations of risk. For example, the probability of infection is calculated as 1.0 minus the probability of not being infected, which is an exponential function of exposure. The population of a compartment may be zero either because operations in the model have not yet transferred a population into that compartment or because the program has rounded off a population of < 1 to zero. If the calculated exposure is zero, the probability of not being infected is calculated as 1.0, and the resulting risk is reported as 0. It is unlikely that there are actually zero pathogens in most compartments; the user has the option of specifying the number of pathogens in each compartment during the input phase of the model run.

A preliminary assessment was made using site-specific data for Site 1. Seventy-five model runs were made to assess the effects on Practices I-III of variations in the parameters chosen (see Section 4.1 above). Several of the parameters were also tested in Practices IV and V. In all model runs, the probability of infection for OFFSITE and DRINKER was calculated as zero. For the subsurface injection option, the probability of infection was calculated as zero in all exposure compartments, because with this application option the parasites are assumed to be deposited below any zone in which exposure could occur. ONSITE exposure occurs as a result of inhalation of dust generated by incorporation of sludge or tilling the soil, or by direct contact with infected soil (U.S. EPA, 1990b). Because pathogens are transferred gradually to the soil compartment during incorporation in Practices I through III, the maximum exposure by direct contact is calculated as occurring when all of the sludge has been incorporated. During incorporation, hourly exposures are less than after incorporation has been completed, so the highest exposure occurs on the day following incorporation. In every model run for Practice I (which requires 24 hours for the sludge to dry before the field is tilled), the maximum probability of infection ONSITE occurred at day 3; whereas for Practices II and III (which do not require the 24-hour wait), the maximum probability of infection ONSITE occurred on day 2. For Practices IV and V, the maximum probability occurred on day 1; in these practices, application and incorporation result in more extensive direct contact than in the agricultural practices. Using default values for the main program variables, the maximum daily probability of infection ONSITE was 0.0191 in Practice I and 0.0027 for Practices II and III. Using the same value for ASCRS in Practices IV and V yielded maximum probabilities of infection of 1.42×10^{-3} and 8.67×10^{-4}, respectively. However, the statutory requirements for D&M sludge allow a maximum of 1 parasite ovum or cyst per g volatile sludge solids (U.S. EPA, 1989). Using the similar value of 1000/kg dry weight for ASCRS, the maximum probability of infection would be 2.85×10^{-4} for Practice IV and 1.73×10^{-4} for Practice V. On the basis of this result, a probability of infection of 1×10^{-4} will be used as a benchmark level for acceptable risk in discussions below.

A preliminary sensitivity analysis of the model was carried out (U.S. EPA, 1990b) to determine the relative sensitivity of model output to variations in input parameters. In this analysis, the values of selected parameters were varied singly, and the calculated numbers of organisms in various compartments were compared. For many parameters, there was no effect on the number of pathogens in the direct contact compartment or in the onsite pond (the model was not sensitive to these parameters). The model was shown to be sensitive to variations in application rate and size of field, which are related to the number of organisms applied; method of application, which determines the surface availability of pathogens; and rate of inactivation of the organisms, which determines the number of pathogens surviving. In the preliminary risk assessment for parasites, the sensitivity of probability of infection to variations in input parameters was analyzed as described in the document Pathogen Risk Assessment for Land Application of Municipal Sludge. Volume I: Methodology and Computer Model (U.S. EPA, 1990b). In this methodology, the change in the input variable of interest is divided by its baseline value ($d\beta/\beta$), and the resulting change in the output of interest is divided by the baseline result (dC/C). A ratio is then taken of the quotients, $S=(dC/C)/(d\beta/\beta)$. For example, when the value of Variable 1, ASCRS, was changed from 5000 to 200, the maximum probability of infection ONSITE was reduced from 0.01907 to 0.00077. Thus $d\beta/\beta$ was -4800/5000 and dC/C was -0.0183/0.01907. The sensitivity coefficient S was -0.96/-0.96 = 1.00. In most cases, the sensitivity coefficient was 0 for one or both relevant exposure compartments; that is, there was no effect of changing the value of the variable. Table 6-1 summarizes the results when there was a response to a change in the value of a variable in Practice I, using site-specific data for Site 1.

These results indicate that at low exposure levels, the probability of infection varies directly (S=1) with the concentration of organisms in the sludge (ASCRS) and soil (APRATE) and with amount of soil ingested or contacted directly (DRECTS). However, further investigation of the relationship between APRATE and probability of infection showed that as APRATE is changed farther from the default value, S diverges from 1. To illustrate this divergence, values of S were calculated for ONSITE, EATER and SWIMMER at various values of APRATE and plotted as a function of APRATE (Figure 6-1).

The value of S varied much more for SWIMMER than for ONSITE when the exponential decay rates were varied. This difference occurs because of the nature of the Poisson distribution used to calculate risk of infection: as the average exposure increases, the fraction of individuals exposed to more than one infective dose increases, yielding a less than proportional increase in infection rate. In addition, the highest ONSITE exposure occurs at day 2 or 3, whereas the highest SWIMMER exposure occurs at day 70; therefore, varying the die-off rate affects the SWIMMER exposure more than the ONSITE exposure. Because the onsite-pond pathogen densities vary according to rainfall events, the relative concentrations of the peaks in concentration change as die-off rate changes. Thus, in some cases (but not all) changes in die-off rate change the day on which the maximum probability of infection occurred.

Overall, the sensitivity analyses of Practices II and III gave results similar to those for Practice I. Practices IV and V do not include an onsite pond, so there are no SWIMMER exposures in these compartments. As with the other practices, there were only small variations in S for ONSITE exposures as input variables were changed.

These results indicated that analysis of input variables other than SUSPND and DECAY would not be productive. Therefore, in subsequent modeling runs, only SUSPND and DECAY were changed.

Variables in Subroutine RAINS were also tested. In this test, a single rainfall event was modeled for simplicity. The largest rainfall used for Site 1, 12.47 cm total rainfall at

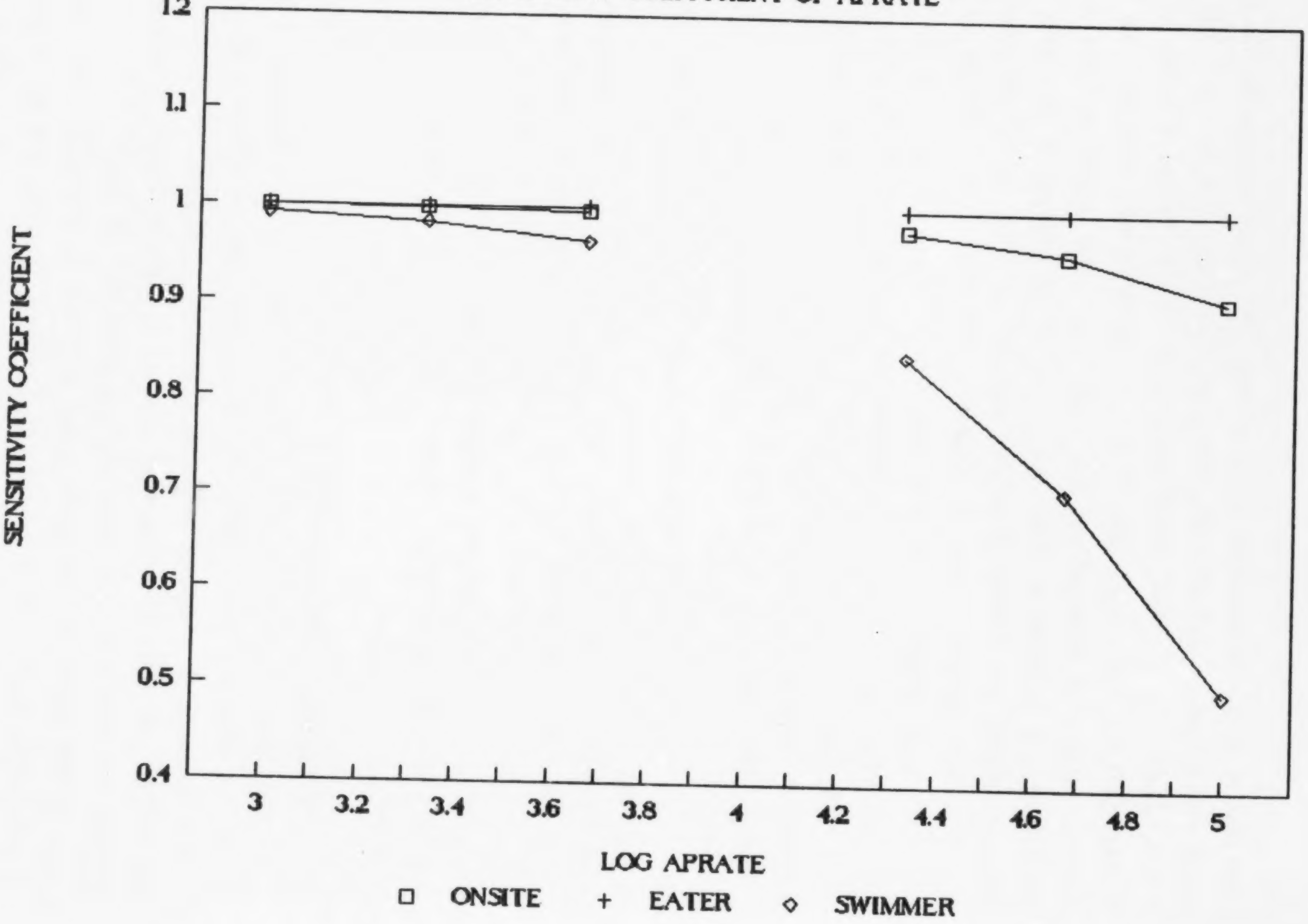
TABLE 6-1

SENSITIVITY COEFFICIENTS OF SITE-SPECIFIC VARIABLES

Variable	Value	Probability of Infection		Sensitivity Coefficient	
		ONSITE	SWIMMER	ONSITE	SWIMMER
Baseline		0.01907	0.1388		
1 ASCRS	200	0.00077	0.0060	1.0	0.997
1 ASCRS	$1.1\text{x}10^4$	0.0416	0.2802	0.978	0.849
2 APRATE	$2.5\text{x}10^4$	0.0470	0.345	0.976	0.941
45 SUSPND	0.001		0.1656		-0.21
R6 DRECTS	0.02	0.00384		1.0	
R6 DRECTS	0.20	0.0378		0.98	
DECAY	-0.0005	0.01819	0.0868	-0.0717	-0.330
DECAY	-0.0001	0.01915	0.1655	-0.0096	-0.439

FIGURE 6-1

SENSITIVITY COEFFICIENT OF APRATE



a duration of 10 hr, was arbitrarily placed at Hour 240. Other variables for the base rainfall were BTLAG = 0.32, CN = 89, AMC = 2, STAD = 0.25, USLEK = 0.32, USLEL = 2.54, USLES = 1.25, USLEC = 0.05 AND USLEP = 1.0. Because a number of the variables (BTLAG, CN, USLEL and USLES) are interdependent, their minimum and maximum values were combined into two model runs. Other parameters were varied independently, as indicated in Table 6-2. None of the changes in parameters for Subroutine RAINS had an effect on ONSITE exposure, and effects on the food consumer (EATER) were minimal, except for changes in SUSPND [P(45)]. Effects on the SWIMMER were variable and somewhat contradictory. Specifying a good soil and a 1% slope (RAIN4L) slightly increased the EATER exposure and reduced transport to the onsite pond. Conversely, increasing the erodibility of the soil by specifying a poor soil and increasing the slope to 7% (RAIN4H) slightly increased both the EATER and SWIMMER exposures. Specifying a moist soil (RAIN6H) or poor ground cover (RAIN11H) markedly increased the SWIMMER exposure.

Both of these conditions would be expected to increase the amount of runoff water relative to transported sediment. In contrast, increasing the resuspension factor SUSPND [P(45)], which describes the transfer of pathogens from soil to runoff water, greatly decreased both the EATER and the SWIMMER exposures. This result implies that sediment transport is more important than runoff water as a transfer route to the pond. In summary, increasing the amount of runoff water increased exposure, but increasing the fraction of soil pathogens suspended in runoff water decreased exposure. The reason for this apparent inconsistency is not clear.

6.2. EXPOSURE COMPARTMENTS

The results of model runs under the various conditions are summarized in Tables 6-3 and 6-4, which give the probability of infection under these conditions at all six sites. Default conditions are compared to changes in SUSPND [P(45)] and die-off rates (LOW and HIGH). No SWIMMER exposures occurred in Practices IV and V because it is assumed that there is no onsite pond collecting runoff from the site.

In these model runs, site-specific values were used for Subroutine RAINS (Section 5), and default values were used for the main program variables, with the exception of

TABLE 6-2

SENSITIVITY TO PARAMETERS OF SUBROUTINE RAINS

FILE NAME	VARIABLE NAME	VARIABLE VALUE	PROBABILITY OF INFECTION ONSITE	PROBABILITY OF INFECTION EATER	PROBABILITY OF INFECTION SWIMMER
RAINBASE			0.019	5.73×10^{-5}	0.274
RAIN4L	BTLAG	1.2	0.019	6.07×10^{-5}	0.190
	CN	40			
	USLEL	2.54			
	USLES	0.12			
RAIN4H	BTLAG	0.2	0.019	5.84×10^{-5}	0.288
	CN	90			
	USLEL	4.76			
	USLES	0.7			
RAIN6L	AMC	1	0.019	5.80×10^{-5}	0.202
RAIN6H	AMC	3	0.019	5.66×10^{-5}	0.312
RAIN7L	STAD	0.2	0.019	5.73×10^{-5}	0.275
RAIN7H	STAD	0.5	0.019	5.73×10^{-5}	0.273
RAIN8L	USLEK	0.1	0.019	5.73×10^{-5}	0.271
RAIN8H	USLEK	0.5	0.019	5.73×10^{-5}	0.278
RAINBASE	USLEC	0.05	0.019	5.73×10^{-5}	0.274
RAIN11H	USLEC	0.5	0.019	5.72×10^{-5}	0.319
RAIN12L	USLEP	0.25	0.019	5.73×10^{-5}	0.271
RAINBASE	USLEP	1.0	0.019	5.73×10^{-5}	0.274
RAINSPL	SUSPND	0	0.019	6.53×10^{-5}	0.287
RAINSPH	SUSPND	0.1	0.019	1.66×10^{-5}	0.176

TABLE 6-3

PROBABILITY OF INFECTION, ONSITE

SITE	PRACTICE	DEFAULT	SUSPND	DIE-OFF LOW	DIE-OFF HIGH
1	I	$1.907x10^{-2}$	$1.907x10^{-2}$	$1.915x10^{-2}$	$1.819x10^{-2}$
	II	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	III	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	IV	$1.424x10^{-3}$	$1.424x10^{-3}$	$6.170x10^{-3}$	$5.934x10^{-3}$
	V	$8.667x10^{-4}$	$8.667x10^{-4}$	$6.190x10^{-3}$	$6.030x10^{-3}$
2	I	$1.907x10^{-2}$	$1.907x10^{-2}$	$1.915x10^{-2}$	$1.819x10^{-2}$
	II	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	III	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	IV	$1.424x10^{-3}$	$1.424x10^{-3}$	$6.170x10^{-3}$	$5.934x10^{-3}$
	V	$8.667x10^{-4}$	$8.667x10^{-4}$	$6.190x10^{-3}$	$6.030x10^{-3}$
3	I	$1.907x10^{-2}$	$1.907x10^{-2}$	$1.915x10^{-2}$	$1.819x10^{-2}$
	II	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	III	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	IV	$1.424x10^{-3}$	$1.424x10^{-3}$	$6.170x10^{-3}$	$5.934x10^{-3}$
	V	$8.667x10^{-4}$	$8.667x10^{-4}$	$6.190x10^{-3}$	$6.030x10^{-3}$
4	I	$1.907x10^{-2}$	$1.907x10^{-2}$	$1.915x10^{-2}$	$1.819x10^{-2}$
	II	$2.616x10^{-3}$	$2.649x10^{-3}$	$2.661x10^{-3}$	$2.592x10^{-3}$
	III	$2.616x10^{-3}$	$2.649x10^{-3}$	$2.661x10^{-3}$	$2.592x10^{-3}$
	IV	$1.424x10^{-3}$	$1.424x10^{-3}$	$6.170x10^{-3}$	$5.934x10^{-3}$
	V	$8.667x10^{-4}$	$8.667x10^{-4}$	$6.190x10^{-3}$	$6.030x10^{-3}$
5	I	$1.907x10^{-2}$	$1.907x10^{-2}$	$1.915x10^{-2}$	$1.819x10^{-2}$
	II	$2.664x10^{-3}$	$2.662x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	III	$2.664x10^{-3}$	$2.662x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	IV	$1.424x10^{-3}$	$1.424x10^{-3}$	$6.170x10^{-3}$	$5.934x10^{-3}$
	V	$8.667x10^{-4}$	$8.667x10^{-4}$	$6.190x10^{-3}$	$6.030x10^{-3}$
6	I	$1.907x10^{-2}$	$1.907x10^{-2}$	$1.915x10^{-2}$	$1.819x10^{-2}$
	II	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	III	$2.665x10^{-3}$	$2.665x10^{-3}$	$2.671x10^{-3}$	$2.592x10^{-3}$
	IV	$1.424x10^{-3}$	$1.424x10^{-3}$	$6.170x10^{-3}$	$5.934x10^{-3}$
	V	$8.667x10^{-4}$	$8.667x10^{-4}$	$6.190x10^{-3}$	$6.030x10^{-3}$

TABLE 6-4

MAXIMUM PROBABILITY OF INFECTION, SWIMMER

SITE	PRACTICE	DEFAULT	SUSPND	DIE-OFF .LOW	DIE-OFF HIGH
1	I	1.388×10^{-1}	1.656×10^{-1}	1.655×10^{-1}	1.093×10^{-1}
	II	9.013×10^{-4}	9.008×10^{-4}	1.102×10^{-3}	5.920×10^{-4}
	III	9.691×10^{-4}	9.686×10^{-4}	1.183×10^{-3}	6.247×10^{-4}
2	I	2.669×10^{-1}	3.572×10^{-1}	3.605×10^{-1}	1.416×10^{-1}
	II	2.433×10^{-2}	5.250×10^{-3}	8.397×10^{-3}	1.407×10^{-3}
	III	6.240×10^{-3}	5.448×10^{-3}	8.649×10^{-3}	1.500×10^{-3}
3	I	1.617×10^{-1}	1.981×10^{-1}	2.057×10^{-1}	1.383×10^{-1}
	II	1.091×10^{-2}	1.090×10^{-2}	1.243×10^{-2}	7.902×10^{-3}
	III	1.180×10^{-2}	1.179×10^{-2}	1.461×10^{-2}	8.212×10^{-3}
4	I	7.357×10^{-2}	9.279×10^{-2}	1.077×10^{-1}	2.413×10^{-2}
	II	3.383×10^{-4}	3.380×10^{-4}	6.206×10^{-4}	1.425×10^{-4}
	III	3.767×10^{-4}	1.425×10^{-4}	6.785×10^{-4}	1.438×10^{-4}
5	I	3.358×10^{-4}	5.386×10^{-4}	9.810×10^{-4}	1.743×10^{-5}
	II	2.930×10^{-5}	2.928×10^{-5}	2.938×10^{-5}	2.896×10^{-5}
	III	2.932×10^{-5}	2.931×10^{-5}	2.940×10^{-5}	2.898×10^{-5}
6	I	4.540×10^{-4}	5.396×10^{-4}	6.694×10^{-4}	1.497×10^{-3}
	II	2.800×10^{-4}	2.797×10^{-5}	4.154×10^{-4}	9.276×10^{-5}
	III	2.803×10^{-4}	2.801×10^{-5}	4.157×10^{-4}	9.284×10^{-5}

FCROP [P(46)]=5x10^{-6}, TCROP [P(68)]=240 and THARV [P(69)]=300. More detailed comparisons of the results are made below.

As a comparison of the effects of application practice on potential human exposures to parasites in land-applied sludge, the results of model runs using site-specific data for Site 1 and practice-specific data for all five practices are presented in Table 6-5. This table shows that ONSITE exposures related to the grazing and feed crop applications are lower than those for field crops, but exposures for residential applications are even lower. Runoff and sediment transport are significantly lower in the grazing and feed crop applications, resulting in a much lower exposure for the SWIMMER. The probability of infection of the food consumer (EATER) is higher for aboveground crops in the residential application than in the application for commercial production of food crops for human consumption.

The effects of site-specific variables on exposure are demonstrated in Table 6-6, which shows the maximum probability of infection at all sites, using practice-specific values for Practice I. The largest effect was on the SWIMMER exposure because the variation in timing of rainfalls had a major effect on the amount of surface runoff and sediment transport moving parasites into the onsite pond. Rainfall times also had an effect on contamination of the crop surface, resulting in slight variations in both ONSITE and EATER exposures.

The effect of timing and amount of rainfall on surface runoff was studied further by using the times and amounts of rainfall events at Site 6 (with infrequent but intense rainfall) along with other site-specific values for Site 1 (with more frequent and more moderate rainfall), and vice versa. When this was done using Practice I, there were no significant changes in maximum probability of infection in the ONSITE or EATER compartments. For SWIMMER, site-specific variables were shown to be significant, but the rainfall pattern was shown to be more significant than soil properties: the maximum probability of infection to the SWIMMER at Site 1 changed from 0.14 to 0.008 when the rainfall pattern of Site 6 was substituted, and the maximum probability at Site 6 changed from 0.0005 to 0.22 when the rainfall pattern of Site 1 was substituted.

6.2.1. ONSITE. The maximum probability of infection ONSITE was essentially the same at all sites, because site-specific variables had little time to act on the number of organisms in the first three days of the model run. The maximum probability of infection at each site,

TABLE 6-5

MAXIMUM PROBABILITY OF INFECTION, SITE 1*

PRACTICE	ONSITE	EATER	SWIMMER
1	1.907×10^2	5.944×10^5	1.388×10^1
2	2.665×10^3	---	9.013×10^4
3	2.665×10^3	---	9.691×10^4
4	1.424×10^3	3.057×10^3	---
5	8.667×10^4	---	---

*Site-specific values for Subroutine RAINS are described in Section 5; main program values were default values, except FCROP [P(46)]=1×10^6, TCROP [P(68)]=240, THARV [P(69)]=300

TABLE 6-6

MAXIMUM PROBABILITY OF INFECTION, PRACTICE I

SITE	ONSITE	EATER	SWIMMER
1	1.907×10^{-2}	5.944×10^{-5}	1.388×10^{-1}
2	1.907×10^{-2}	6.341×10^{-5}	2.669×10^{-1}
3	1.907×10^{-2}	6.015×10^{-5}	1.617×10^{-1}
4	1.888×10^{-2}	6.279×10^{-5}	7.357×10^{-2}
5	1.889×10^{-2}	6.282×10^{-5}	3.358×10^{-4}
6	1.907×10^{-2}	6.341×10^{-5}	4.540×10^{-4}

[*] Site-specific variables are described in Section 5; main program variables were default values, except FCROP [P(46)]=5×10^{-6}, TCROP [P(68)]=240, THARV [P(69)]=300.

using default values for SUSPND and die-off rates and a parasite density of ASCRS=5000, was: Practice I, 0.191; Practices II and III, 0.0027; Practice IV, 0.0014; and Practice V, 0.00087.

6.2.2. Food Consumer (EATER). The calculated probability of infection of the food consumer (EATER) as a result of consuming the crop was $<10^{-16}$ in every model run in which the default values for CROP [P(66)] (aboveground crop) and FCROP1 [(P46)] were used. However, when the on-ground crop was modeled [P(66) = 0] and the crop was harvested at the unrealistically early time of 300 hours, the probability of infection immediately after harvesting was 0.068. When a below-ground crop was modeled [P(66) = -1], the probability of infection immediately after harvesting at 300 hours was 0.146. The reduced probability of infection via aboveground crops reflects the assumption that the exposure of aboveground crops to contaminated soil (by blown dust or splashing during a rain) is much less than the exposure of on-ground or below-ground crops (by direct contact with soil).

The amount of soil associated with the crop was significant in determining the probability of infection. The default conditions include a value of $1x10^{-8}$ for FCROP1 [P(46)], the fraction of sludge remaining on the aboveground crop and consumed by the food eater. Because of dilution of applied sludge by surface soil, that fraction represents 20 g of soil on the entire crop surface, or about $2x10^{-4}$ g/crop unit (tomato). If FCROP1 is increased to represent 0.1 g soil remaining on each crop unit at harvesting, the probability of infection per serving of the aboveground crop became $6.47x10^{-5}$ if the crop was harvested at 300 hours and $8.91x10^{-6}$ if the crop was harvested at 150 days after application of sludge. For subsequent model runs, P(46) was increased to $5x10^{-6}$ to ensure that there would be a significant exposure in the EATER compartment.

Harvesting of on-ground and below-ground crops after 3600 hours (150 days) was also modeled. This time was chosen to represent a crop planted 30 days after sludge application and harvested 120 days later. In this case, the below-ground crop gave a risk of infection of 0.018/serving, compared to 0.0083/serving for the on-ground crop. These results are summarized in Table 6-7.

Table 6-8 gives a comparison of infection probabilities for food consumers under site-specific conditions for all six sites. The time specified for harvesting in this comparison

TABLE 6-7

MAXIMUM PROBABILITY OF INFECTION BY CONSUMPTION OF CONTAMINATED CROPS

Conditions	g soil/ crop unit	Harvest at 300 hours	Harvest at 150 days
Aboveground	0.0002	$< 1.0\text{x}10^{-8}$	$< 1.0\text{x}10^{-8}$
Aboveground	0.1	$6.47\text{x}10^{-5}$	$8.91\text{x}10^{-6}$
On-ground	0.2	$6.80\text{x}10^{-2}$	$8.34\text{x}10^{-3}$
Below-ground	0.2	0.146	0.018

TABLE 6-8

MAXIMUM PROBABILITY OF INFECTION OF FOOD CONSUMER (EATER)*

		Type of Crop		
Practice	Site	Aboveground	On-ground	Below-ground
I	1	5.94×10^{-5}	6.80×10^{-2}	1.46×10^{-1}
	2	6.34×10^{-5}	7.24×10^{-2}	1.55×10^{-1}
	3	6.02×10^{-5}	6.88×10^{-2}	1.48×10^{-1}
	4	6.28×10^{-5}	7.17×10^{-2}	1.54×10^{-1}
	5	6.28×10^{-5}	7.18×10^{-2}	1.54×10^{-1}
	6	6.34×10^{-5}	7.24×10^{-2}	1.55×10^{-1}
IV	1	3.10×10^{-3}	3.06×10^{-3}	1.64×10^{-3}
	2	3.20×10^{-3}	3.16×10^{-3}	1.70×10^{-3}
	3	3.10×10^{-3}	3.06×10^{-3}	1.64×10^{-3}
	4	3.16×10^{-3}	3.13×10^{-3}	1.68×10^{-3}
	5	3.10×10^{-3}	3.06×10^{-3}	1.64×10^{-3}
	6	3.10×10^{-3}	3.06×10^{-3}	1.64×10^{-3}

* Site-specific values for Subroutine RAINS are given in Section 5; main program values were default values, except FCROP1 [P(46)]=5×10^{-6}, TCROP [P(68)]=240, THARV [P(69)]=300.

was 300 hours. Results are shown only for Practices I and IV because the calculated probabilities of infection in Practices II, III and V were $< 10^{-16}$ at all sites. These results show that site-specific variables had little effect on the calculated risk; the variation in infection probability within each type of crop and each practice was less than 10%. The probability of infection from consumption of aboveground crops was calculated to be approximately 50-fold higher for home crops than for the agricultural application. In contrast, despite the fact that the modeled application rate for Practice IV was 2.5 times the rate for Practice I, the calculated probabilities of infection from consuming on-ground crops were lower for home gardens by 2 to 2.5-fold and lower for consuming below-ground crops by approximately 100-fold. These results must reflect differences between the practices in distribution of sludge pathogens above, on and below the surface.

Land access and crop use restrictions are applied on the basis of the extent of pathogen reduction effected by the treatment process (U.S. EPA, 1989). Class A treatment is assumed to render sludge microbiologically harmless, requiring no waiting period before exposure is allowed. Class B and C treatments require a waiting period of 18 months after application before aboveground and on-ground food crops can be grown, and a 60-month waiting period before below-ground crops can be grown (18 months if there are no parasites in the sludge). The waiting period for grazing on sludge-amended pasture is 1 month for Class B treatment and 2 months for Class C treatment. In the computer model, the class of treatment is entered in response to a prompt. A waiting period based on the land use practice is then assigned to the model run. Exposure (time of harvest) is not allowed before the waiting period has elapsed. Thus the operator is forced to choose a time of harvest [P(69)] that exceeds the waiting period. The effect of time of harvesting on the probability of infection by ingestion of aboveground crops was assessed by varying P(69) in a series of model runs, using the default application rate and 5000/kg as the parasite density. The results are presented in Table 6-9. The values given for months 15 and 18 for the aboveground crop are extrapolations; the model gives a result of 0 because at these times the concentration of parasites on the crop is calculated to be $< 1 \times 10^{-9}$/g, which is assigned the value of 0. These results show that a waiting period may be unnecessary for consumption of aboveground crops, and a waiting period of 18 months should provide adequate protection (probability of infection $< 1 \times 10^{-4}$/serving) for ingestion

TABLE 6-9

VARIATION OF EATER RISK WITH TIME OF HARVESTING

MONTH	ABOVEGROUND	BELOW-GROUND
0	7.439×10^{-5}	1.729×10^{-1}
1	4.628×10^{-5}	1.156×10^{-1}
2	2.699×10^{-5}	6.914×10^{-2}
3	1.632×10^{-5}	4.240×10^{-2}
6	4.502×10^{-6}	1.188×10^{-2}
9	1.242×10^{-6}	3.290×10^{-3}
12	3.195×10^{-7}	8.477×10^{-4}
15	$< 8\times10^{-8}$	2.351×10^{-4}
18	$< 2\times10^{-8}$	6.247×10^{-5}

of root crops.

6.2.3. **SWIMMER.** As indicated by trial runs with bacteria (U.S. EPA, 1990b), the most significant source of exposure was the surface runoff pond. A peak in probability of infection for the SWIMMER occurred after each rainfall, which transported significant amounts of contaminated sediment into the onsite pond (Figure 6-2). The maximum probability of infection for the SWIMMER in Practice I, 0.139, was observed to occur on day 70, after the heavy rainfall beginning at hour 1650. In Practices II and III the maximum probability of infection for the SWIMMER occurred on day 66, at a level of 0.00090 in Practice II and 0.00097 in Practice III. Practices II and III limit the amount of surface runoff and sediment transport because of the extent of ground cover characterizing these practices. Extensive mulching of soil not covered by crop plants in Practice I would also be expected to reduce the amount of transport to the onsite pond by a small amount.

The maximum probability of infection for the SWIMMER in the onsite pond was dependent on site-specific variables. The number of organisms transferred to the pond by surface runoff and sediment transport depended on both the extent of rainfall and the elapsed time during which the organisms died off in the surface soil before they were transported. The maximum probability at each site and for each practice, using default values for SUSPND and die-off rates, is given in Table 6-10.

The time course of infection probability for Practice I at each site is displayed graphically in Figure 6-3. It is clear from these results and the rainfall data presented in Section 5 that the maximum probability of infection as a result of exposure in the onsite pond is closely related to the timing and total amount of rainfall and to the farming practice.

FIGURE 6-2

SWIMMER EXPOSURE BY PRACTICE, SITE 1

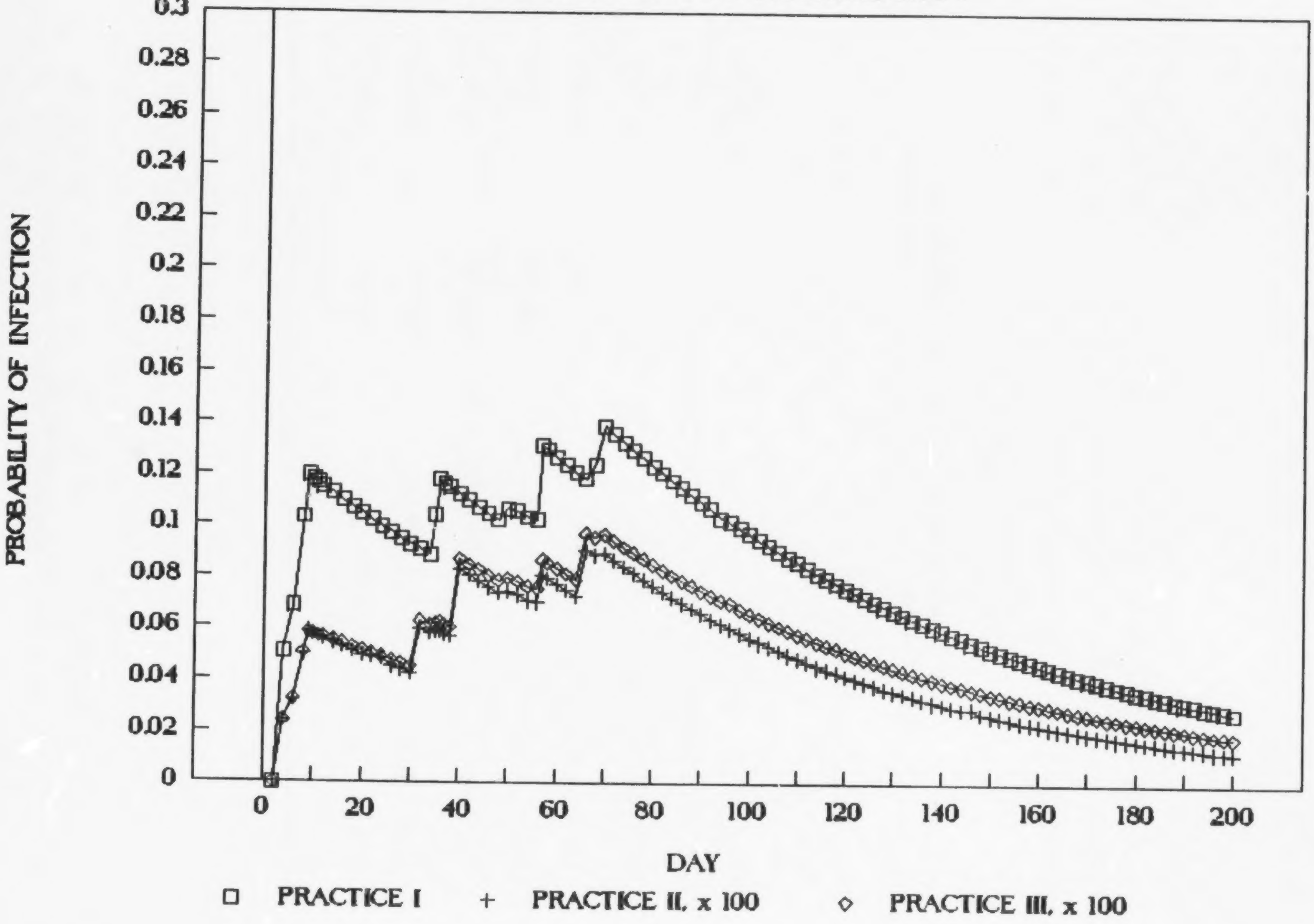


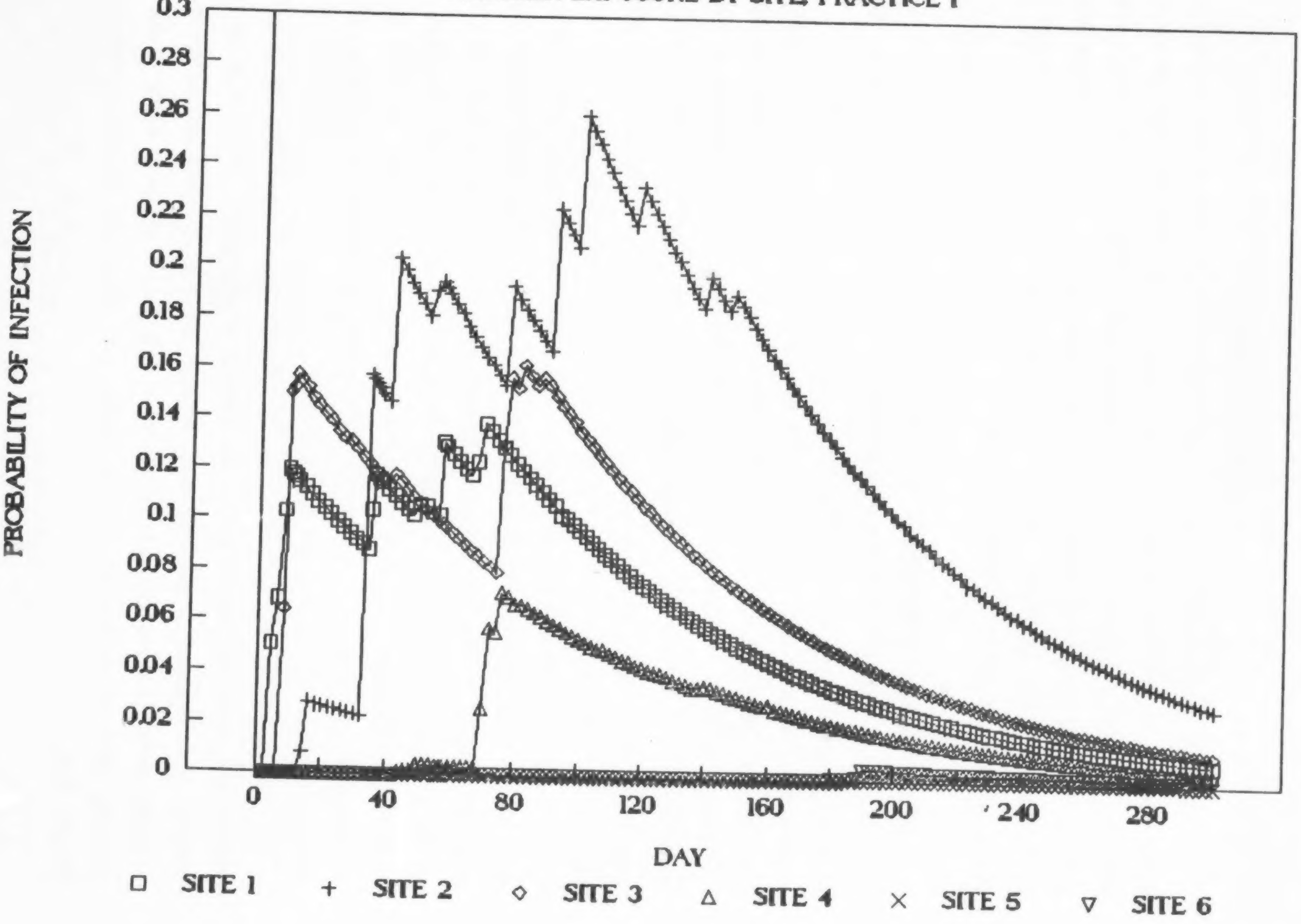
TABLE 6-10

MAXIMUM PROBABILITY OF INFECTION BY EXPOSURE TO RUNOFF WATER (SWIMMER)

	Practice		
Site	I	II	III
1. Anderson Co., TN	1.39×10^{-1}	9.01×10^{-4}	9.69×10^{-4}
2. Chaves Co., NM	2.67×10^{-1}	2.43×10^{-2}	6.24×10^{-3}
3. Clinton Co., IA	1.62×10^{-1}	1.09×10^{-2}	1.18×10^{-2}
4. Highlands Co., FL	7.36×10^{-2}	3.83×10^{-2}	3.77×10^{-2}
5. Kern Co., CA	3.36×10^{-4}	2.93×10^{-5}	2.93×10^{-5}
6. Yakima Co., WA	4.54×10^{-4}	2.80×10^{-4}	2.80×10^{-4}

FIGURE 6-3

SWIMMER EXPOSURE BY SITE, PRACTICE I



7. CONCLUSIONS

Although detailed data on survival and transport of parasites in soil are lacking, the model appears to confirm the general observations in the literature that parasites are persistent, justifying land-use restrictions. Model runs implied that restrictions on the consumption of below-ground crops may be overly conservative. Reports of offsite infection by parasites in sludge-amended soil are rare; model runs confirm the low probability of offsite infection except by uncontrolled surface runoff.

7.1. SENSITIVITY ANALYSIS

Model runs showed that within narrow limits, the probability of infection by parasites as a result of exposure to soil contaminated with sewage sludge is proportional to the concentration of organisms in the sludge, the amount of sludge applied and the amount of contaminated soil to which the individual is exposed, either by casual contact or ingestion of food grown in the contaminated soil. Direct proportionality of response to exposure level is not maintained over a wide range of concentrations, however, because the probability of infection is calculated by a Poisson distribution, which is an exponential function of exposure rather than a proportional one. Variations in the probability of infection can be extrapolated from variations in parasite concentrations up to a probability of about 0.1; the departure from linearity is 5% at a probability of 0.093 and 10% at a probability of 0.176. Many of the parameters of the model seemed to have little bearing on the probability of infection, apparently because they ultimately had no effect on the number of organisms to which the human receptor was exposed in each exposure compartment, or because they exerted their effect on survival or transport after the maximum probability of infection had occurred.

The probability of infection was sensitive to the rate of inactivation or die-off of the parasite ova, cysts and oocysts and to the method of application. Subsurface application resulted in no exposure to any individual, because the ova, cysts and oocysts are modeled as being unable to move significant distances in soil. Future revisions of the model should probably allow for redistribution of pathogens from subsurface soil into surface soil (see Section 8.2).

7.2. ONSITE EXPOSURES

Significant onsite exposures were calculated in all practices when 5000/kg dry weight was used as the parasite concentration in the sludge. The greatest risk, approximately 0.02 per day, was associated with Practice I, application of sludge for production of commercial crops. These calculations imply that the field worker who inadvertently ingests soil during daily activity on the sludge application site is at significant risk of infection by parasites. The results imply that there should be a waiting period before routine daily activity on the site. The length of the waiting period should depend on the initial application rate and pathogen concentration as well as the die-off rate of the parasite; in the model runs reported here, the probability of infection ONSITE in Practice I was >0.01 for more than 30 days and $>10^{-7}$ for about 27 months.

The maximum risks of infection calculated in domestic applications were lower (0.0014 for Practice IV and 0.0009 for Practice V), but not low enough to be protective. However, it must be noted again that a concentration of 5000 parasites/kg was used in the model runs, whereas U.S. EPA regulations for D&M sludge call for a limit of 1 parasite/g volatile sludge solids (U.S. EPA, 1989), or approximately 1000/kg dry weight. It is assumed that incorporation in these practices is done by hand or with power tools rather than by farm machinery; therefore, the calculated exposures include direct exposure to non-incorporated sludge. During incorporation, the parasite concentration is rapidly reduced by dilution in soil, and by the end of the second day, the extrapolated probability of infection is below 1×10^{-7} in both practices. In summary, it appears that a probability of infection greater than the arbitrary benchmark value of 1×10^{-4} is likely during application and incorporation of D&M sludge. A person engaged in these activities could probably reduce the risk by wearing a protective mask and washing thoroughly before handling food.

7.3. SEDIMENT TRANSPORT AND SURFACE RUNOFF

The most significant potential source of infection was exposure to runoff water and transported sediment after rainfall. Rainfall events were modeled as being able to transport contaminated soil from the field to the onsite pond, where the suspended or particle-bound parasites accumulated. A swimmer in the pond was therefore exposed to the parasites, either by ingestion of ova, cysts or oocysts or by infective larvae penetrating the skin. Model runs indicated that it would be prudent to limit access to runoff water and sediment from a sludge-amended field, either by mulching to reduce runoff, ditching and/or diking to contain the runoff or restricting access to any onsite ponds receiving runoff.

7.4. OFFSITE EXPOSURES

No health hazard was indicated as a result of offsite transport of parasites by droplet aerosols or by wind-blown dust. This may be a model limitation caused by over-simplification of the Gaussian-plume aerosol transport subroutine in the model, or it may reflect a very low concentration or probability of transport of viable parasites in aerosols. Because it was assumed that transport of ova, cysts and oocysts to groundwater does not occur, no risk from consumption of groundwater from a drinking water well was demonstrated.

7.5. WAITING PERIOD

Practice-specific waiting periods are required by the U.S. EPA Pathogen Reduction Requirements (U.S. EPA, 1989) before access to sludge-amended land or consumption of crops grown thereon. For exposure comparisons, a probability of infection of $1x10^{-4}$ was tentatively chosen as a benchmark for sufficient protection of human health (Section 6.1). Using this benchmark value, the default values for application rate and die-off rate, and a parasite density of 5000/kg, the initial maximum probability of infection for aboveground crops was $<1x10^{-4}$ (Table 6-8). This result indicates that a waiting period may not be necessary for consumption of aboveground crops contaminated with 0.1 g soil per crop unit. A waiting period of 18 months appeared to be adequate for below-ground crops, whose consumption is currently forbidden for 5 years after sludge application. In all cases, the probability of infection depended on the amount of soil consumed with the crop. The default value for fraction of soil adhering to the aboveground crop is very low; using this value (approximately 20 mg/crop unit), the calculated probability of infection of the food consumer was $<10^{-16}$, indicating that a waiting period would not be required for a low level of surface contamination. Similarly, the probability of infection depends on the concentration of pathogens in the sludge when it is applied. Therefore, the appropriate waiting period should probably be variable, depending not only on intended land use, as is currently true, but also on sludge application rate and pathogen concentration. In calculating a safe waiting period, conservative assumptions should be made about amounts of soil ingested with crops.

8. RESEARCH NEEDS

8.1. INFORMATION NEEDS FOR PARASITES

As indicated in Tables 3-3 and 4-1, data on the concentration of parasite ova, cysts and oocysts in sewage sludge after treatment and on survival of the organisms in sludge-amended soil are sparse. A review of published literature reveals that data are available for only a few indicator organisms.

Distribution of pathogens in soil or groundwater is poorly understood. This model assumes random distribution of pathogens in environmental media, a commonly-made assumption that is probably frequently violated. Another obvious data gap, illustrated by this methodology and model development, is the degree of survival and transport of pathogens in the environment. Information on the fate of parasites in groundwater and subsurface soil is extremely limited. The concentration and survival rates of pathogens leaching through soil into groundwater are unavailable for protozoa and helminths (U.S. EPA, 1986). In addition, the survival of these organisms in soil depends strongly on prior conditions of treatment. For example, mild heating or digestion alone may have little effect on viability of Ascaris ova, whereas mild heating of digested sludge rapidly destroys the ova (Pike et al., 1988).

Characterizing the average or typical concentration of viable ova in treated sludge may not be of great significance because the probability of infection is directly related to the concentration of parasites in the particular sample or batch of treated sludge. Each community's treatment system and source material will be different in some details from the ideal or average system characterized in research studies. The treated sludge from individual treatment systems can be characterized more accurately by direct counts than by assumptions that they conform to a typical concentration distribution. However, it is difficult to characterize the survival of parasites in soil in each individual case, and a well-characterized range of survival under defined conditions would be useful.

Reimers et al. (1986) concluded that, since Ascaris and Toxocara are typically present in most municipal sludges applied to land, the following information is needed to clarify associated health risks: (1) survival of resistant stages of parasites (ova and cysts) in soil following land application; (2) effects of sewage-treatment method, application method, soil type, climate, and land use on survival; and (3) degree of risk to humans and animals based on field situations.

Reimers et al. (1990) recommend further work in the areas of (1) determining the stabilization conditions needed to produce sludges meeting PFRP criteria; (2) investigating the feasibility of using combined treatment processes, such as digestion followed by lagoon and/or drying bed storage, to inactivate pathogens in sludges processed at small Publicly Owned Treatment Works; (3) determining whether petroleum hydrocarbons would inactivate pathogens in petroleum-contaminated sludges; and (4) selecting appropriate controls for studies of Ascaris egg survival in different types of sludges.

Further research on pathogen exposure pathways and infectious doses will facilitate the predictive accuracy of this model and its successors. Especially useful will be:

- Data on the relation of die-off rate of different parasites to moisture, temperature, method of application and previous sludge treatment. No single organism is really adequate to represent all other parasites. Ascaris can serve as a "worst case" in most instances, but, for example, some protozoa are much smaller and thus are more likely to be transported through soil and in aerosols. Data suggest that moisture and temperature would probably have significant effect on parasite survival, but the one conclusion reached following such a field study is that there is no statistically significant correlation between parasite egg concentration and environmental parameters (Leftwich et al., 1988b).
- More detailed quantitative information on any protection provided by crop cover. It has been shown that subsurface injection of sludge increases the survival of parasite ova and cysts, but quantitative data on relative effects of grass, hay, truck crops or forests on parasite survival are lacking.
- Data allowing a mathematical description of die-off as a function of environmental conditions. Some authors indicate that environmental conditions play an essential role in determining the die-off rate of parasites, whereas others (Grenfell et al., 1986; Young, 1983) see no statistically significant effects. It is likely that a variety of confounding variables have obscured the effects of easily-measured environmental parameters on die-

off rates. With sufficient study, the effects of environmental conditions on survival may become more obvious.

In summary, the following research priorities are recommended to allow development of a definitive risk assessment for parasites in land-applied sludge:

For Helminths:

- Standard quantitative methods for examining helminths in sludge and soil samples and in liquid droplet and dry particulate aerosols;
- Data on transport in water, soil and aerosols;
- Die-off rates in water, soil and aerosols;
- The relationship of those decay rates to environmental conditions, previous sludge treatment, method of sludge application and various effects of crop cover.

For Protozoa:

- Standard quantitative methods for examining protozoa in sludge and soil samples and in liquid droplet and dry particulate aerosols; and
- Quantitative data on occurrence and survivability of protozoa in treated sludge.

If results indicate that protozoa survive in sludge, the following additional research needs become a priority:

- Data on transport in water, soil and aerosols;
- Die-off rates in water, soil and aerosols;
- The relationship of those decay rates to environmental conditions, previous sludge treatment, method of sludge application and various effects of crop cover.

8.2. MODEL DEVELOPMENT

The current version of the Sewage Sludge Pathogen Risk Assessment model is not adequate to address some of the properties of parasite survival in soil. In particular, it has been noted that cycles of freezing and thawing may kill parasite ova more rapidly than exposure to a constant temperature at either extreme of the cycle (Leftwich et al., 1988a).

The model calculates a daily average temperature for each day of the model run, but it does not address the diurnal temperature cycle which can result in subfreezing temperatures at night on days with an average temperature above freezing. It should be possible to program a diurnal cycle into the temperature calculation subroutine and flag for a freeze-thaw cycle. The flag can in turn result in decreasing the population of viable parasites by a fraction specified by default or by the user as one of the operating parameters.

Mathematical descriptions of the die-off of parasite ova and cysts as a function of temperature and moisture are not yet adequate to allow construction of algorithms in the model for die-off rates. However, it appears that a simple relationship between temperature and die-off rate of ova may not occur (Ferris et al., 1978; Grenfell et al., 1986; Young, 1983), and the equation used to calculate die-off rate will probably have to be of a different form than that currently used for bacteria and viruses.

In the present version, the model does not allow for direct contact with sludge during incorporation in Practices I, II and III. Instead, it is assumed that all exposures during incorporation occur via inhalation of dry aerosols generated by the machinery used to incorporate the sludge. It might be more reasonable to include inadvertent ingestion of unincorporated sludge in these practices, as occurs in Practices IV and V.

The model assumes that tilling will not disturb the soil below 15 cm, so parasites injected into subsurface soil are not transferred to surface soil. However, plowing is deeper than tilling and would be expected to redistribute subsurface soil. Some transfer factor could be added to the model to allow for redistribution of pathogens from subsurface to surface soil when the field is plowed.

As described in Section 3 above, there are significant differences in size and probably in survival between helminths and protozoa, and it might be prudent to include the option to model transport of protozoa in groundwater. Future revision of the Pathogen Risk Assessment Model might include providing separate options for helminths and protozoa, with separate sets of default values, or a flag to enable or disable Subroutine GRDWTR, the groundwater transport subroutine.

The present version of the Pathogen Risk Assessment Model does not include an onsite pond in Practice V, the home lawn application. For a better description of sludge use on public parks and golf courses, which are more likely to have ponds, it might be beneficial to add the option for existence of a pond onsite. For even more flexibility, the user could be asked to specify which exposure calculations to print in the output table.

The limits of Subroutine RAINS should be further characterized to establish operating boundaries for input variables. These boundaries could be set by having the program return a warning message and possibly revise the input data to a value that would not cause the program to crash.

Limitations in offsite transport subroutines may limit accuracy of the model, but constraints on the size of a model able to run on a personal computer make it unlikely that more sophisticated routines can be added. For example, sophisticated air dispersion models are large and complex and could probably not be added to the current model. Adding the capacity to model more than one windstorm (the current model limit) would probably be feasible without making the model too unwieldy. It is likely that further analysis of the model using other pathogens will reveal additional areas in which the model can be improved.

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APPENDIX
MODEL OVERVIEW

Five sludge management practices, representing land application and D&M management options, are included in the present model and are numbered I-V. They are listed in Table A-1 and illustrated in Figures A-1 through A-5. Two of the practices use heat-dried or composted sludge for residential purposes and three use liquid sludge for commercial farming operations. Since each of these two types of sludge represents a wide range of sludge treatment possibilities, the extent of treatment or conditioning prior to land application must be approximated for each case (i.e., the pathogen concentration in the applied sludge must be specified). The computer model represents the compartments and transfers among compartments of the five management practices. The compartments are the various locations, states or activities in which sludge or sludge-associated pathogens exist; they vary to some extent among practices. In each compartment, pathogens either increase, decrease or remain the same in number with time, as specified by "process functions" (growth, dieoff or no population changes) and "transfer functions" (movement between compartments). The population in each compartment, therefore, generally varies with time and is determined by a combination of initial pathogen input, "transfer functions" and "process functions." The populations of pathogens in the compartments representing human exposure locations (designated with an asterisk in Figures A-1 through A-5 and in Table A-2), together with appropriate intake and infective dose data, are used to estimate human health risk.

Although each practice listed in Table A-1 is different, all five practices share common characteristics. All compartments that appear in one or more of the five sludge management practices are listed in Table A-2. Those compartments with an asterisk represent exposure sites for the human receptor:

- 3* inhalation or ingestion of emissions from application of sludge or tilling of sludge/soil;
- 5* inhalation or ingestion of windblown or mechanically generated particulates;
- 6* swimming in a pond fed by surface water runoff;

TABLE A-1

COMPARTMENTS INCLUDED IN THE SLUDGE MANAGEMENT PRACTICES

Compartment Name and Number	Liquid Sludge Management Practices			Dried/Composted Sludge Management Practices	
	I	II	III	IV	V
Application	1	1	1	1	1
Incorporation	2	2	2		
Application/Tilling Emissions	3*	3*	3*	3*	3*
Soil Surface	4	4	4	4	4
Particulates	5*	5*	5*	5*	5*
Surface Runoff	6*	6*	6*		
Direct Contact	7*	7*	7*	7*	7*
Subsurface Soil	8	8	8	8	8
Groundwater	9	9	9		
Irrigation Water	10	10	10		
Soil Surface Water	11	11	11	11	11
Offsite Well	12*	12*	12*		
Aerosols	13*	13*	13*		
Crop Surface	14	14	14	14	14
Harvesting	15		15	15	
(Commercial) Crop	16*			16*	
Animal Consumption		17	17		
Meat		18*	18*		
Manure		19	19		
Milk		20*	20*		
Hide		21	21		
Udder		22	22		

*Indicates exposure compartment

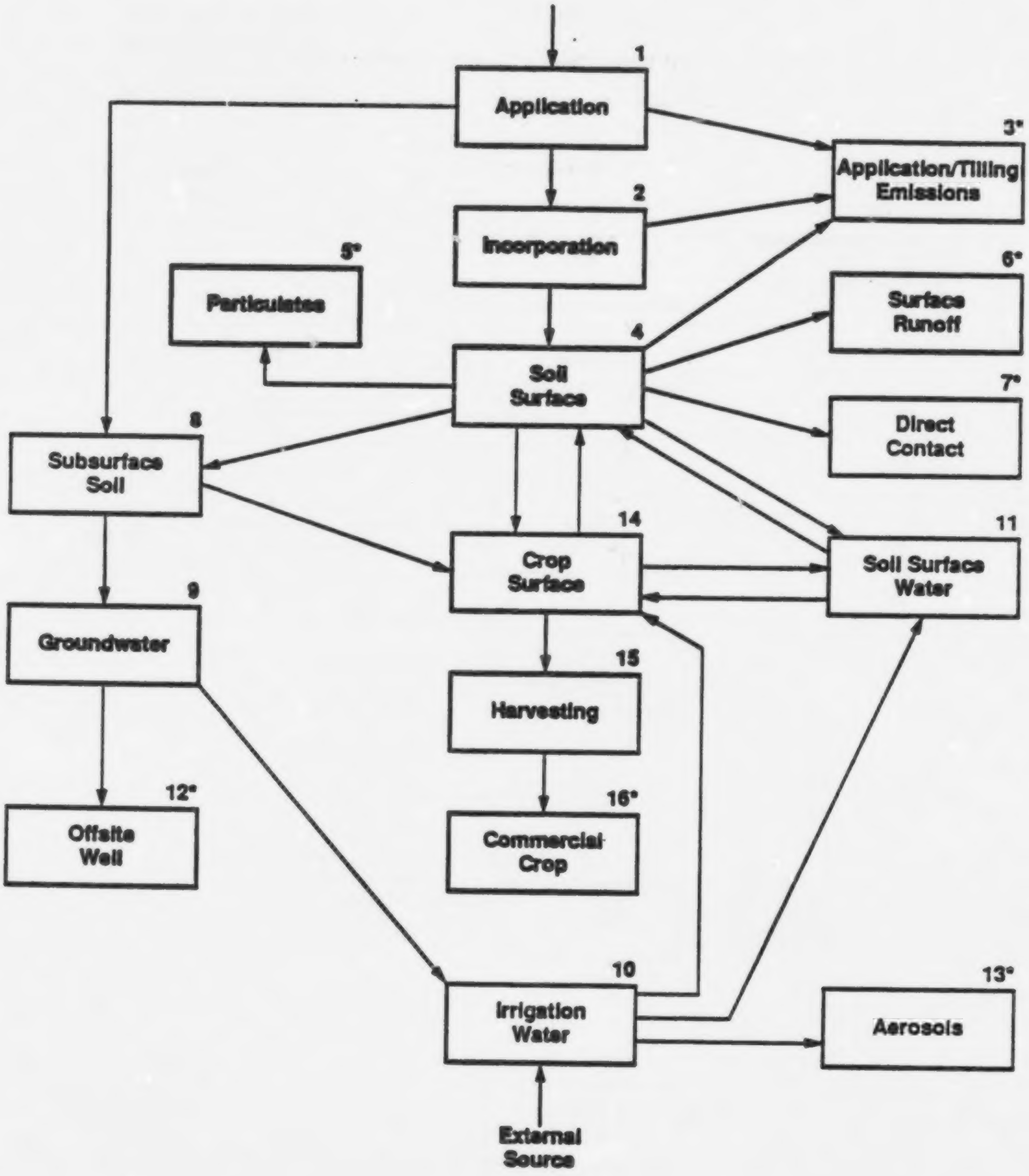

1
Application
2
Incorporation
3*
Application/Tilling Emissions
4
Soil Surface
5*
Particulates
6*
Surface Runoff
7*
Direct Contact
8
Subsurface Soil
9
Groundwater
10
Irrigation Water
11
Soil Surface Water
12*
Offsite Well
13*
Aerosols
14
Crop Surface
15
Harvesting
16*
Commercial Crop
External Source

FIGURE A-1

Input/Output Diagram for Practice I – Application of Liquid Sludge for Production of Commercial Crops for Human Consumption

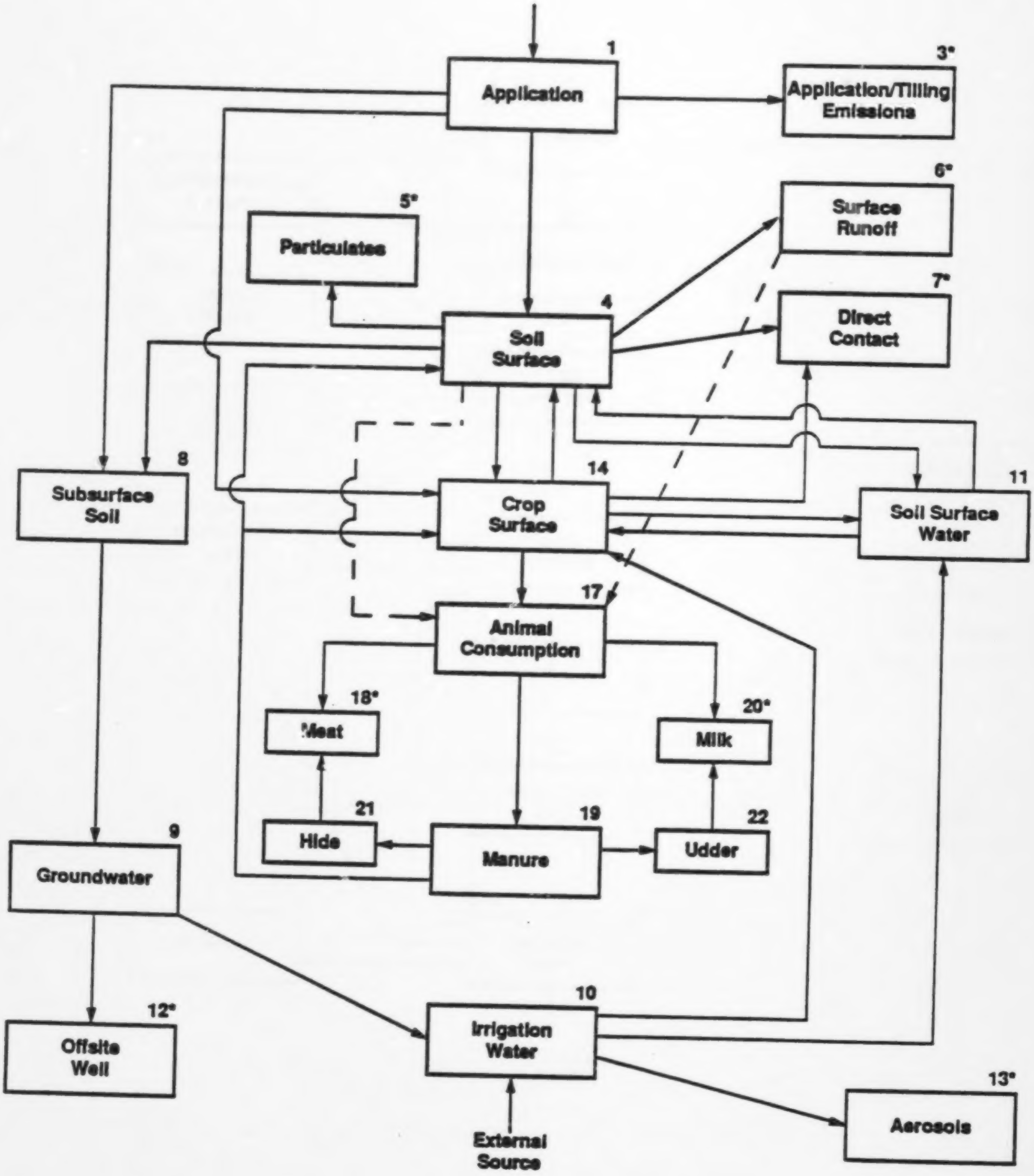

1
Application
3*
Application/Tilling Emissions
5*
Particulates
6*
Surface Runoff
7*
Direct Contact
4
Soil Surface
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
17
Animal Consumption
18*
Meat
20*
Milk
21
Hide
19
Manure
22
Udder
9
Groundwater
12*
Offsite Well
10
Irrigation Water
13*
Aerosols
External Source

FIGURE A-2

Input/Output Diagram for Practice II – Application of Liquid Sludge to Grazed Pastures

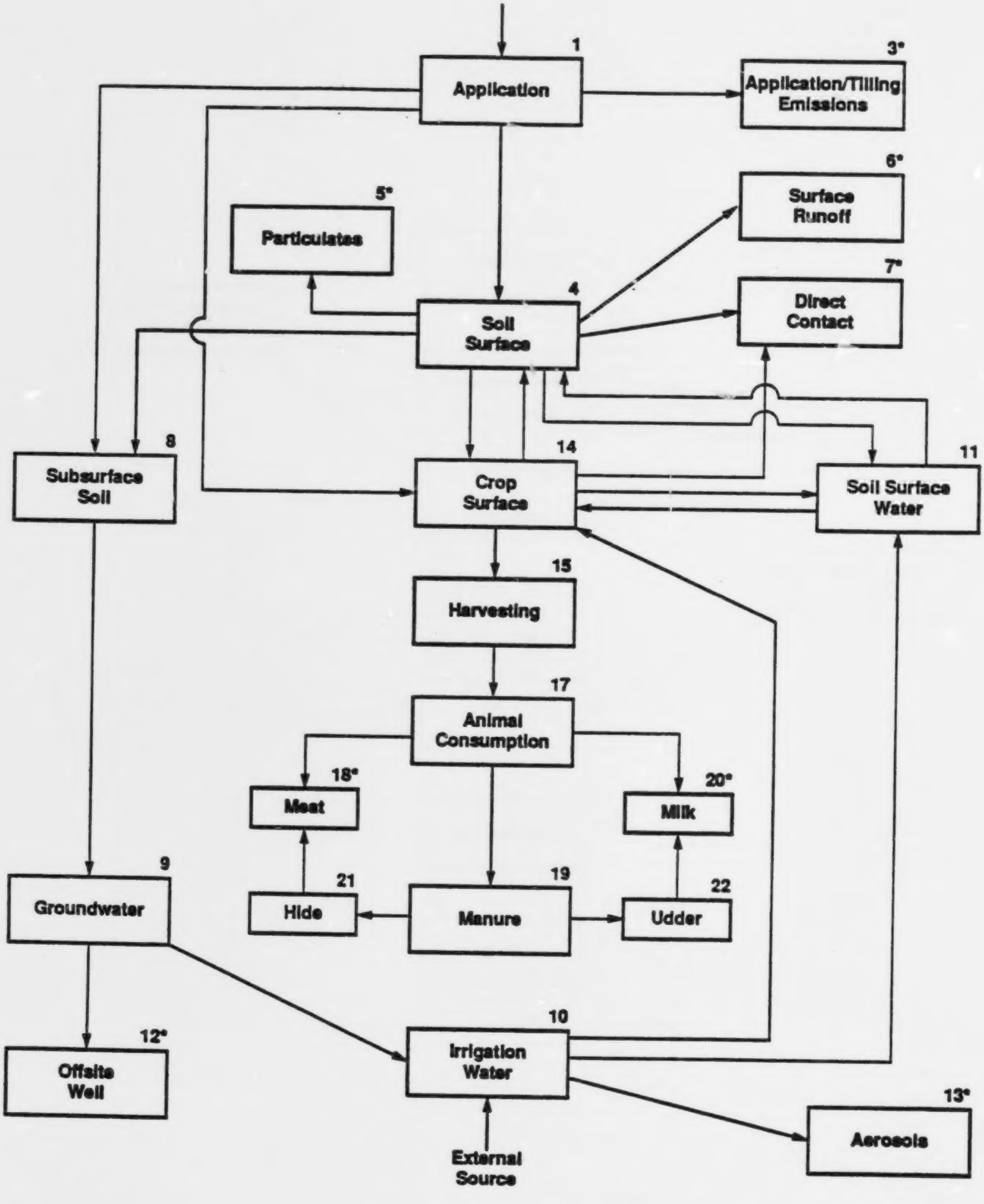
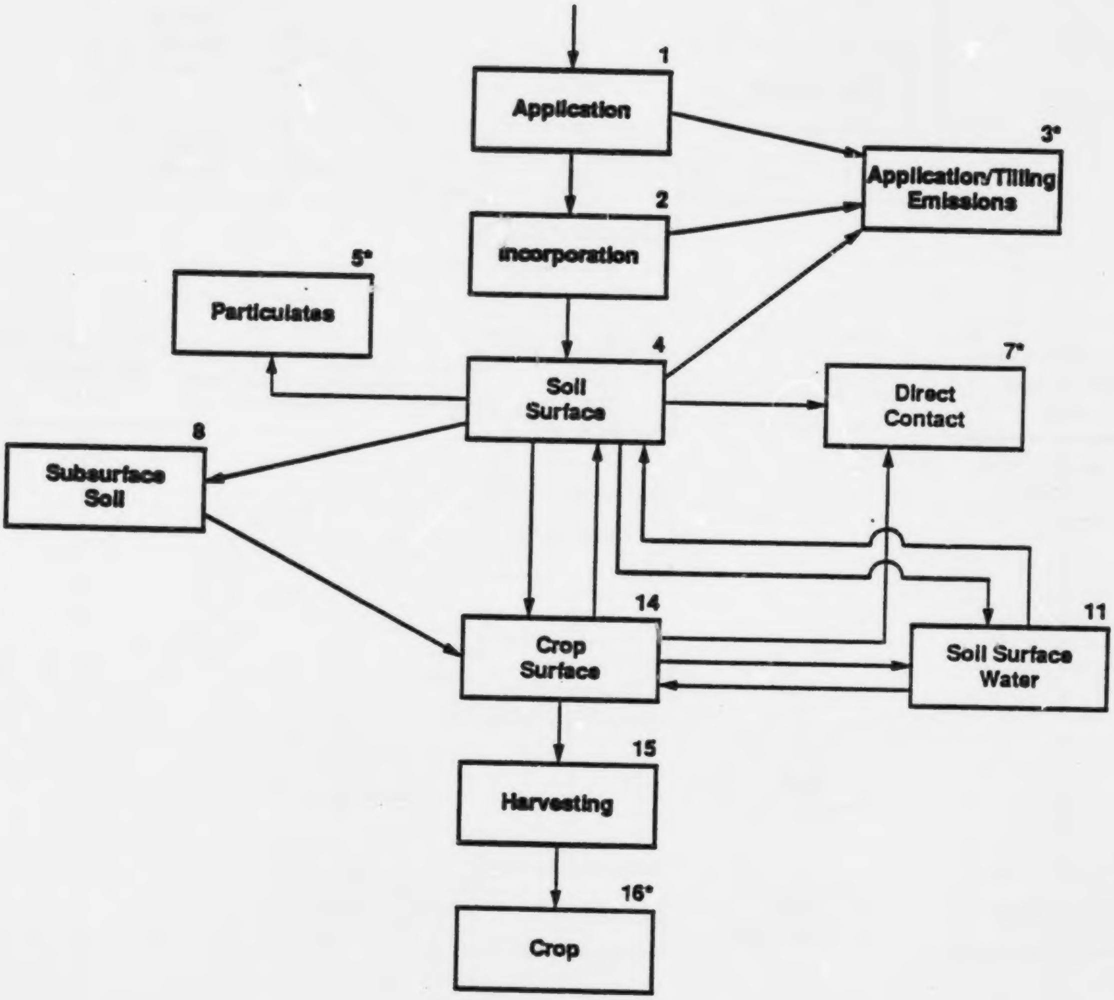

1
Application
3*
Application/Tilling Emissions
6*
Surface Runoff
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
15
Harvesting
17
Animal Consumption
18*
Meat
20*
Milk
9
Groundwater
21
Hide
19
Manure
22
Udder
10
Irrigation Water
12*
Offsite Well
13*
Aerosols
External Source

FIGURE A-3

Input/Output Diagram for Practice III – Application of Liquid Sludge for Production of Crops Processed before Animal Consumption



1
Application
3*
Application/Tilling Emissions
2
Incorporation
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water
15
Harvesting
16*
Crop

FIGURE A-4

Input/Output Diagram for Practice IV – Application of Dried or Composted Sludge to Residential Vegetable Gardens

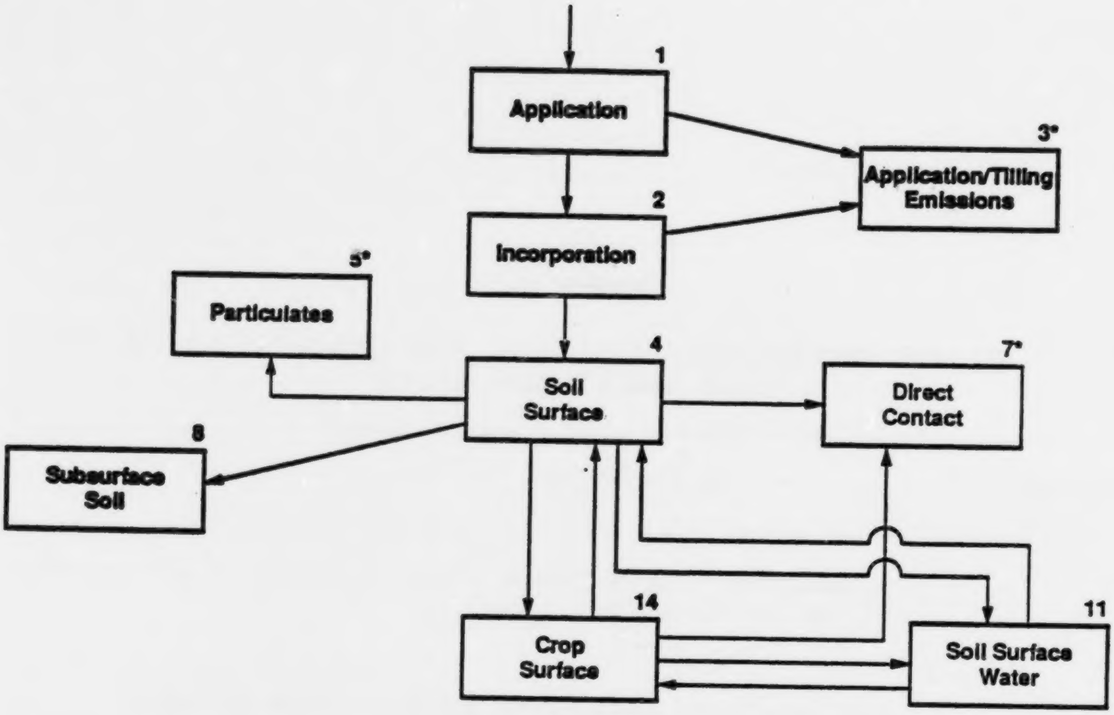

1
Application
3*
Application/Tilling Emissions
2
Incorporation
5*
Particulates
4
Soil Surface
7*
Direct Contact
8
Subsurface Soil
14
Crop Surface
11
Soil Surface Water

FIGURE A-5

Input/Output Diagram for Practice V – Application of Dried or Composted Sludge to Residential Lawns

TABLE A-2

SLUDGE MANAGEMENT PRACTICES AND DESCRIPTIONS IN LAND APPLICATION MODEL

PRACTICE	DESCRIPTION
I	Application of Liquid Treated Sludge for Production of Commercial Crops for Human Consumption
II	Application of Liquid Treated Sludge to Grazed Pastures
III	Application of Liquid Treated Sludge for Production of Crops Processed before Animal Consumption
IV	Application of Dried or Composted Sludge to Residential Vegetable Gardens
V	Application of Dried or Composted Sludge to Residential Lawns

*Two types of sludge are used in this model - liquid and dried/composted. The extent of treatment or conditioning prior to application is variable and must be determined for each case.

- 7* direct contact with sludge-contaminated soil or crops (including grass, vegetables, or forage crops);
- 12* drinking water from an offsite well;
- 13* inhalation and subsequent ingestion of aerosols from irrigation;
- 16* consumption of vegetables grown in sludge-amended soil;
- 18* consumption of meat or
- 20* consumption of milk from cattle grazing on or consuming forage from sludge-amended fields.

The first 14 compartments, most of which are common to all practices, are described below.

APPLICATION (1) represents the application of sludge to a field (default size 10 ha) or to a yard or garden of specified size. Liquid sludge may be applied by spread-flow techniques, by spray, or by subsurface injection. The application rate and pathogen concentrations are variables to be entered by the user of the model. During spread-flow and spray application, sludge will be spread thinly on the soil, where it will be subject to drying, heating and solar radiation, thus losing the protective benefits provided by bulk sludge. It is assumed, therefore, that inactivation will occur at a rate characteristic of the organism in soil at 5°C above the ambient temperature (Brady, 1974; USDA, 1975). It is also assumed that liquid sludge is absorbed by the upper 5 cm of soil surface during this time. The default time period for transfer from APPLICATION (1) to INCORPORATION (2) is 24 hours, which allows a field treated with liquid sludge to dry sufficiently to plow or cultivate. If the injection option is chosen, the liquid sludge goes directly to SUBSURFACE SOIL (8) at hour 10. During spray application of liquid sludge or application of dry composted sludge, droplets or loose particulates may become airborne. Liquid aerosols are modeled by a Gaussian-plume air dispersion model that calculates the downwind concentration of airborne particulates. Dry particulate emissions are calculated using models for generation of dust by tilling or mechanical disturbance of soil. Both are represented as transfers from APPLICATION (1) to APPLICATION/TILLING EMISSIONS (3).

INCORPORATION (2) involves the mixing, by plowing or cultivation, of the sludge and sludge-associated pathogens evenly throughout the upper 15 cm of soil. Process functions associated with this compartment are the same as for the relevant pathogen type in soil. Particulate emissions generated by cultivation are represented by a transfer from INCORPORATION (2) to APPLICATION/TILLING EMISSIONS (3) beginning at hour 24, extending for enough time to cultivate the field (at a rate of 5 ha/hr) or till the garden or lawn (at a rate of 0.002 ha/hr). At the end of this time, all remaining pathogens are transferred to SOIL SURFACE (4).

APPLICATION/TILLING EMISSIONS (3*) is an exposure compartment that receives the dust, or suspended particulates, generated by application or by the tilling of dried sludge or sludge-soil mixture. It also receives aerosols generated by spray application of liquid sludge. All process functions associated with this compartment are incorporated in the aerosol subroutines. Exposure in this compartment is by inhalation but, as in all inhalation exposures, model simplification limits the exposure to the pathogens assumed to be ingested after the inhaled dust or aerosol spray is trapped in the upper respiratory tract, swept back to the mouth by ciliary action and swallowed.

SOIL SURFACE (4) describes the processes occurring in the upper 15 cm (Practices I, IV and V) or upper 5 cm (Practices II and III) of the soil layer. Microbes are inactivated at rates characteristic for moist soil at 5°C above the chosen ambient temperature (Crane and Moore, 1986; Kibbey et al., 1978). Transfers from SOIL SURFACE (4) occur by wind to WIND-GENERATED PARTICULATES (5), at a time chosen by the user, by surface runoff and sediment transport after rainfall events to SURFACE RUNOFF (6), by a person walking through the field or contacting soiled implements or clothing or by other casual contact to DIRECT CONTACT (7), by leaching after irrigation or rainfall to SUBSURFACE SOIL (8), by resuspension during irrigation or rainfall to SOIL SURFACE WATER (11), or at harvest to CROP SURFACE (14).

WIND-GENERATED PARTICULATES (5*) describes the airborne particulates generated by wind. Process functions are the same as for the organism in air-dried soil at the ambient temperature (Crane and Moore, 1986; Kibbey et al., 1978). The exposed individual is standing in the field or at a user-specified distance downwind from the field during a windstorm. The wind-generated exposure is calculated from user-specified values for duration and severity of the windstorm (default values, 6 hr at 18 m/sec (40 mph)).

SURFACE RUNOFF (6*) is an exposure compartment describing an onsite pond containing pathogens transferred from SOIL SURFACE (4) by surface runoff and sediment transport after rainfall. These processes are described by a separate subroutine. Inactivation rates in this compartment are characteristic of microbes in water and are much lower than rates for soil. Water is removed from the pond by infiltration and recharge of the groundwater aquifer, but it is assumed that no microbes are transferred by this process. The human receptor is an individual who incidentally ingests 0.1 L of contaminated water while swimming in the pond. This compartment is also an exposure compartment for cattle drinking 20 L of water daily from the pond (Practice II).

DIRECT CONTACT (7*) is the exposure compartment for a worker or a child less than 5 years old who plays in or walks through the field, yard or garden, incidentally ingesting 0.1 g of soil or vegetation at the daily geometric mean concentration of pathogens. This human receptor represents the worst-case example of an individual contacting contaminated soil or soiled clothing or implements. No process functions are associated with this compartment because it is strictly an exposure compartment.

SUBSURFACE SOIL (8) describes the processes and transfers for pathogens in the subsurface soil between 5 or 15 cm depth and the water table. It also serves as the incorporation site for subsurface injection of liquid sludge. Process functions in SUBSURFACE SOIL (8) are the same as for moist soil at the ambient temperature. The transfer from SOIL SURFACE (4) occurs after each rain or irrigation event as a result of leaching from the soil surface. The time of transfer is calculated by dividing the depth of rainfall or irrigation by the infiltration rate. Transfer to GROUNDWATER (9) is arbitrarily set at one hour later. At present, the relation between unsaturated water flow and subsurface transport has not been well-established. Thus, this model lacks a satisfactory subroutine to describe pathogen transport from the subsurface soil to groundwater. Instead, user-specified variables are used to describe the fraction of pathogens transferred from SOIL SURFACE (4) to SUBSURFACE SOIL (8) and from SUBSURFACE SOIL to GROUNDWATER.

GROUNDWATER (9) describes the flow of pathogens in the saturated zone. Process functions are the same as for other water compartments. Transfers occur to IRRIGATION WATER (10) if the water is needed for irrigation or to OFFSITE WELL (12*) if the water is used for drinking. The number of pathogens transferred to

IRRIGATION WATER (10) is based on the concentration of pathogens in the groundwater compartment and the total depth of irrigation. The transfer to OFFSITE WELL (12) is described by a modification of the subsurface solute transport model of van Genuchten and Alves (van Genuchten and Alves, 1982). Because microbes in suspension are passively transported by bulk water flow and interact with soil particles by adsorption and desorption, they behave similarly enough to dissolved chemicals that existing solute transport models can be used to describe their fate in the saturated zone (Gerba, 1988).

IRRIGATION WATER (10) describes the transfers for pathogen-contaminated water used for irrigation. No processes are associated with this compartment because it is intended as a transition compartment. Irrigation of the field, lawn or garden takes place a user-specified number of times each week. This irrigation water may come from either an onsite well fed by GROUNDWATER (9) or from an outside source of treated, liquid sludge. The default conditions vary by practice. In either case, AEROSOLS (13) are generated unless a non-spray option is chosen. Spray irrigation is the default since it would be most likely to cause a significant exposure to workers or offsite persons. In addition to aerosol emissions, irrigation transfers pathogens to CROP SURFACE (14) and to SOIL SURFACE WATER (11).

SOIL SURFACE WATER (11) represents any irrigation water or rainfall in contact with the ground prior to infiltration. This compartment describes the temporary suspension of pathogens in such a water layer and their subsequent transfer to CROP SURFACE (14) or to SOIL SURFACE (4). Process functions are the same as for other water compartments.

OFFSITE WELL (12*) is the exposure site for a human receptor drinking 2 L/day of contaminated water whose pathogens have been transported through groundwater. Process functions are the same as for groundwater. The groundwater transport subroutine supplies the concentration of pathogens in the well at a user-specified distance from the source. No transfers out of the compartment are specified because it is an exposure compartment only.

AEROSOLS (13*) describes fugitive emissions from spray irrigation, which occurs at a default rate of 0.5 cm/hr for 5 hr. The source of irrigation water producing AEROSOLS can be an onsite well (i.e.,GROUNDWATER) or liquid sludge. A Gaussian-plume model is used to calculate concentrations of airborne microbes downwind. The human receptor is an onsite worker or a person offsite who is exposed during the time of irrigation.

CROP SURFACE (14) describes contamination of vegetable or forage crops by transfer of user-specified amounts to or from SOIL SURFACE (4), from IRRIGATION WATER (10), or to or from SOIL SURFACE WATER (11). Process functions are not well characterized but are assumed to be influenced by drying, thermal inactivation and solar radiation; they are thus most characteristic of pathogens in surface soil.

These preceding 14 compartments are common to most of the five practices modeled. The following descriptions of the five management practices help clarify the differences among the practices.

Practice I: Application of Liquid Treated Sludge for Production of Commercial Crops for Human Consumption.

Liquid sludge may be applied as fertilizer/soil conditioner for the production of agricultural crops for human consumption or for animal forage or prepared feed. Both existing (40 CFR 257.3-6) and proposed (U.S. EPA, 1989) regulations prohibit direct application of sewage sludge to crop surfaces. Therefore, this model practice is designed for a single application of liquid sludge, which is incorporated into the soil before the crop is planted. Regulations also require various waiting periods before the planting of crops that will be consumed uncooked by humans. These restrictions, however, are optional in the model and can be tested.

Vegetables can be grown aboveground, on-ground or below-ground. These are represented by tomatoes, zucchini and carrots, respectively. At HARVESTING (15) time, all pathogens remaining on CROP SURFACE (14) are transferred to HARVESTING (15), which represents a single harvest of all of the crop. The same process functions apply as in CROP SURFACE (14). The crop is held for 24 hours before being processed. The number of pathogens is then transferred to COMMERCIAL CROPS (16*), the compartment in which further processing takes place. The number of pathogens/crop unit following processing is calculated in this compartment and is the figure used in the vegetable-exposure risk calculations. A 24-hour pathogen exposure is computed by Subroutine VEG. Pathogen concentrations are determined as number/crop unit for each sludge management practice. Before being consumed, vegetables normally are processed in some way. Included in the program is a series of user-selectable processing steps. The user has the option of choosing any or all processing steps and of specifying some conditions within processing steps. The human receptor is a person who consumes minimally prepared vegetables (washed, but not peeled or cooked) at a rate of 81 g tomatoes, 80 g zucchini or 43 g carrots per eating occasion (Pao et al., 1982).

Practice II: Application of Liquid Sludge to Grazed Pastures.

In this practice liquid sludge is applied as fertilizer, soil conditioner and irrigation water for the production of forage crops for pasture. This model practice is designed for repeated applications of liquid sludge, initially on a field with a standing forage crop used for pasture. It is assumed that spray irrigation will be used because this method is effective for delivering large amounts of sludge to a large area. In this way, the pasture is also used as a final treatment and disposal system for the treated sludge. The irrigation rate, the total weekly depth and the number of times per week can be specified by the user. A sludge solids concentration of 5% is assumed.

The model assumes that each hectare of pasture supports 12 head of cattle, although both area and herd size may be varied. This may be a higher density than is the common practice for fields that receive no irrigation, but with adequate irrigation, sufficient forage is expected to be produced. Current and proposed regulations require various waiting periods before animals can be grazed. These requirements can also be tested by the model.

ANIMAL CONSUMPTION (17) describes the ingestion of CROP SURFACE (14) by cattle grazing in the pasture. Transfers from ANIMAL CONSUMPTION (17) are to MEAT (18*), MANURE (19) and MILK (20*).

MEAT (18*) is the compartment describing transfer of pathogens from ANIMAL CONSUMPTION (17) to meat. The human receptor is assumed to consume 0.256 kg of meat daily (U.S. FDA, 1978). Contamination of meat by gut contents during slaughter or by systemic infection by sludge-borne pathogens can be modeled. The model allows for inactivation of pathogens in meat by cooking, assuming reasonable cooking times and temperatures.

The production and consumption of milk from cattle pastured on the sludge-amended field are modeled when the dairy cattle option is chosen. The default condition is for consumption of raw milk because commercial production of milk poses an extremely small hazard of exposure to pathogens. In the model, contamination from dirty utensils and careless handling are combined as a transfer from the manure-contaminated udder [MANURE (19)], which occurs at each milking. All three pathogens can enter milk by this route. MILK (20*) is the compartment describing production and consumption of milk from cattle pastured on the sludge-amended field when the dairy cattle option is chosen. The default condition models the consumption of raw milk that has been stored for 24 hours. In exposure calculations, it is assumed that the human receptor consumes 2 kg milk/day, roughly three times the national average milk consumption (U.S. FDA, 1978).

Practice III: Application of Liquid Treated Sludge for Production of Crops Processed before Animal Consumption.

In this practice, liquid sludge is applied as fertilizer, soil conditioner and irrigation water for the production of forage crops to be processed and stored for animal feed. This model practice is designed for repeated applications of liquid sludge, initially on a field with a standing forage crop. It is assumed that spray irrigation will be used for the application of liquid sludge, because this method is effective for delivering large amounts of sludge to a large area. In this way, the field is also used as a final treatment and disposal system for the treated sludge. The rate, the total weekly depth and the number of irrigations per week can be changed by the user. A sludge solids concentration of 5% is assumed. The risks to the human receptor are similar to those for the preceding practice, i.e., exposure through meat or milk, in addition to direct contact with the forage grown in the field.

Practice IV: Application of Dried or Composted Sludge to Residential Vegetable Gardens.

Dried or composted treated sludge may be sold or given away to the public as a bulk or bagged product for use as fertilizer or soil conditioner for the production of domestic garden crops for human consumption. Although some studies have shown that composting is highly effective in removing pathogens from sludge (Wiley and Westerberg, 1969), other studies have shown that bacterial pathogens may grow in dried or composted sludge to concentrations of 1×10^6 organisms/kg dry weight (U.S. EPA, 1988). Exposure of individuals to materials used in home gardening would be expected to be more frequent than exposure in a commercial agricultural setting. Therefore, this practice would be expected to pose a greater risk of infection. This model practice is designed to describe the application of dried or composted treated sludge, which is incorporated into the soil before the crops are planted.

Vegetables can be grown aboveground, on-ground or below-ground. These are represented by tomatoes, zucchini and carrots, respectively. The user may specify the proportions of above-ground, on-ground and below-ground crops in the garden. At HARVESTING (15) time, all pathogens remaining on CROP SURFACE (14) are transferred to HARVESTING (15). The same process functions apply as in CROP SURFACE (14). The crop is held for 24 hours before being processed. The number of pathogens is then transferred to CROP (16*), the compartment in which further processing takes place. The number of pathogens/crop unit following processing is calculated in this compartment and is the figure used in the vegetable-exposure risk calculations. A 24-hour pathogen exposure is computed by Subroutine VEG. Pathogen concentrations are determined as number/crop unit for each sludge management practice. Pathogen concentrations are determined as number/crop unit.

Before being consumed, vegetables normally are processed in some way. Included in the program is a series of user-selectable processing steps. The user has the option of choosing any or all processing steps and of specifying some conditions within processing steps. In the default condition, the human receptor is a person who consumes minimally prepared vegetables (washed, but not peeled or cooked) at a rate of 81 g tomatoes, 80 g zucchini or 43 g carrots per eating occasion (Pao et al., 1982).

Practice V: Application of Dried or Composted Sludge to Residential Lawns.

Dried or composted treated sludge may be made available to the public as a bulk or bagged product to be sold or given away for use as fertilizer or soil conditioner for the preparation of a seed bed for domestic lawns. Individuals engaged in preparing a seed bed for a lawn are likely to come into contact with the soil and any additives used to improve the seed bed. If the soil or the additives contain pathogens, this practice would be expected to pose a risk of infection. This model practice is designed to describe the application of dried or composted treated sludge, which is incorporated into the soil before the lawn is seeded.

The main exposure in this practice is for the lawn worker or for a child younger than 5 years old who plays in or walks through the lawn site, incidentally ingesting soil or crop surface at the daily geometric mean concentration of pathogens. This human receptor represents the worst-case example of an individual contacting contaminated soil or soiled clothing or implements. Before all pathogens have been transferred to SOIL SURFACE (4), exposure is at the pathogen concentration found in undiluted sludge whereas, after the transfer, the concentration is that calculated for the soil-sludge mixture.

After 840 hours, the time assumed necessary for the lawn to require mowing, the lawn is mowed weekly, and a fraction of the pathogens associated with CROP SURFACE (14) are transferred to DIRECT CONTACT (7). It is assumed that the person mowing the lawn is exposed by inhalation and/or ingestion at each mowing.

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